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RADIATION DAMAGE TO SILICON SOLAR CELLS

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

GODDARD SPACE FLIGHT CENTER

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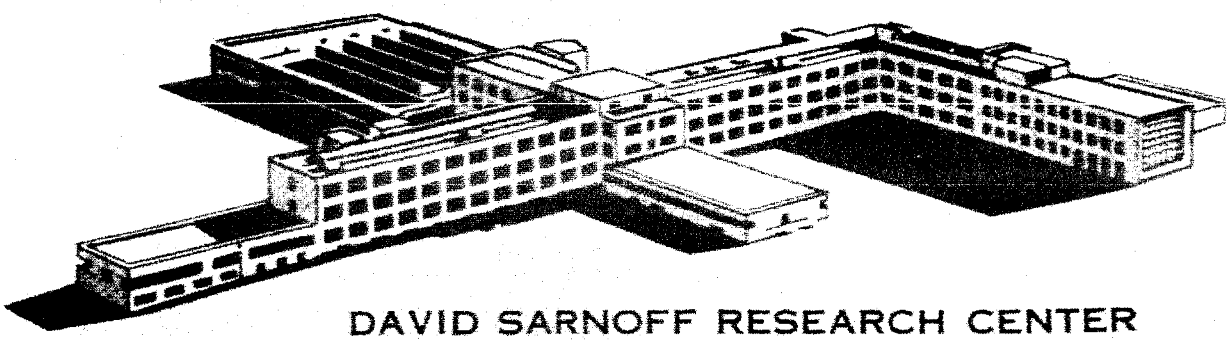

DAVID SARNOFF RESEARCH CENTER

PRINCETON, NEW JERSEY

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GODDARD SPACE FLIGHT CENTER

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ABSTRACT

This report summarizes the results of a study of the effects of radiation on silicon solar cells. Proton, electron and ultraviolet irradation of both solar cells and a small selection of possible cover materials is described. From measurements of the photovoltaic response (spectral and current-voltage characteristics) and the minority carrier lifetimes as functions of bombardment a number of the damage parameters were determined. The results are presented in terms of the "critical flux" (the flux required for 25% loss in conversion efficiency) and wherever possible the product of defect introduction rate and recombination cross section is also given. For electron irradiation the damage rates vary strongly with bombarding energy; from just above the displacement threshold (at around 200 kev) to 800 kev there is a change of $10^3 - 10^4$ in the damage rate. For proton irradiation the damage rates are quite insensitive to bombarding energy from 1 to 20 Mev. The effects of bombardment on minority carrier lifetime and diffusion length are described. Analysis of the spectral response before and after irradiation indicates (1) most of the photovoltaic response occurs in the base region of the cells and (2) virtually all of the damage occurs to the base response. There is a significant difference in damage rates of "p on n" compared with "n on p" cells, the "p on n" being consistently more damage susceptible. The difference drops from a factor of over 1000 at electron bombarding energies near 200 kev to a factor of 2-3 at proton energies of 19 Mev. The approximate operating lifetime in the Van Allen belts is calculated from the proton and electron damage data. No effect of ultraviolet irradiation on the solar cells was found. Except for sapphire and quartz the cover materials and one sample of clear epoxy used to bond covers to cells discolored severely under ultraviolet irradiation.

PURPOSE

The purpose of this contract is to study the effect of protons, electrons and ultra-violet radiation on silicon solar cells of various efficiencies and construction.

FACTUAL DATA

I. INTRODUCTION

Silicon photovoltaic cells have come into widespread use for solar energy conversion, and in particular for power supplies in satellites. In common with most semiconductor materials and devices the electrical properties of these cells are very sensitive to small amounts of nuclear radiation. As recently as three years ago, however, in ignorance of the existence of the Van Allen radiation belts, the best estimates of the radiation-damage limited lifetimes of solar cells in space vehicles ranged upwards from 10^4 years. The discovery of these trapped radiation belts in 1958[1] by Van Allen and co-workers necessitated a review of all such estimates; for uncoated solar cells mounted on the outer surface of a satellite the revised estimates of the operating lifetime varied greatly, with lifetime predictions as short as a few days being common.

There are two major uncertainties in calculating what the lifetime of a typical solar cell power supply will be. The first and larger of these is a persistent lack of information on the intensity and energy spectrum of the trapped particles; the second is a lack of information on the behavior of any given solar cell under completely specified radiation fluxes. To reduce these uncertainties there is now a considerable effort underway (largely supported by NASA) to acquire more complete data on the Van Allen belts, and studies of radiation damage of solar cells have been and are being conducted by groups here at RCA Laboratories, at Bell Telephone Laboratories, Space Technology Laboratories, Transitron, and others.

The result of this effort has been something of an improvement on both problems. Irradiation of silicon cells has been carried out at a number of particle energies, for both protons and electrons.

Although the results exhibit fairly large fluctuations from cell to cell which cause roughly a factor of two uncertainty in the operating lifetime the situation represents a major improvement over what was possible relatively recently.

The analysis which was carried out under the present contract has resulted in several instances in a better understanding of the operation of the silicon photovoltaic cell. These include the finding that the response occurs principally in the base of the cell, with only a small fraction coming from the surface layer (in a great many cells there is no surface response whatever). It has also been shown that the radiation damage occurs primarily in the base of the cell. This is consistent with the first finding, and has the additional utilitarian value of simplifying analysis of the damage data. Early photovoltaic damage measurements made under this contract indicate that the dependence of damage on bombardment flux was in disagreement with previous results on electron-voltaic effect damage rates. Subsequent analysis has resolved the disagreement; the differences can be fully explained in terms of the spectral distribution of the illumination and the deterioration rates at different wavelengths.

The differences between "p on n" and "n on p"* cell damage rates that were noted earlier in electron-voltaic effect studies have been extended and confirmed for the photovoltaic effect. The result has been a sizeable development effort aimed at producing n/p cells having performance as good as the best current p/n cells.

This report is intended to provide a comprehensive description of the work that was done on electron and proton bombardment of silicon photovoltaic cells at RCA Laboratories. To some extent a portion of both the introductory discussion and experimental results have appeared in previous reports. They are repeated here for completeness and clarity.

II. THE VAN ALLEN RADIATION FLUX

The results of satellite studies conducted over the past two years[1-5] indicate that there is a relatively stable belt of trapped protons with an intensity peak located over the equator at an altitude of roughly 3500 km and a belt of trapped electrons having a principal maximum intensity at an altitude of 25,000 km and a secondary intensity peak at 12,500 km.[2] The origin of the trapped particles is not completely agreed upon, but the best suggestions are that the trapped protons result from beta decay of cosmic ray albedo neutrons and the trapped electrons are ejected from the sun during solar storms. Both hypotheses are subject to some doubt at present.

The best existing data on intensity and energy distribution of trapped protons comes from several recent high-altitude missile flights. The apogee of these flights was far short of the peak of the inner belt (altitudes of 1200 to 1800 km were reached) and consequently it is not completely safe to extrapolate the distributions that were observed at these altitudes to determine the flux at the center of the belt. The intensity where is was measured at the lower regions is only ≈ 10% – 20% of the maximum value at the peak of the belt. Figure 1 shows the results of two reported measurements of the proton energy distribution.[3,4]

*Hereafter in this report "p on n" will be denoted p/n and "n on p" by n/p.

The lowest proton energy for which data is available is roughly 8 Mev, as indicated in Fig. 1. The lack of data at lower energies makes it impossible to calculate the damage that would occur in an unprotected cell in the proton belt, but if a suitable transparent cover that is thick enough to stop 8 Mev protons without becoming rapidly discolored is provided, the flux penetrating to the cell can be determined, and from this the damage rate can be estimated. Sapphire is being widely considered as a cell cover for satellite applications. Thirty mils of sapphire for example, has a stopping power of 18 Mev for protons.

There is a considerable discrepancy between the early "space probe" measurements of the proton intensity[1] and the recent measurements reported in References (3) and (4). In a later section of this report the operating lifetimes of typical solar cells in the Van Allen belts will be calculated, and for this purpose the differences in reported proton intensity will resolved in favor of the recent emulsion measurements.

The energy spectrum of electrons in the outer belt has also been reported. According to the data of Reference (5) the ratios of the intensities above three different energies are $N(E > 45\ \text{kev}) : N(E > 450\ \text{kev}) : N(E > 4.5\ \text{Mev}) = 1 : 10^{-2} : 10^{-5}$ and the total ionization is 2×10^{11} ev/sec-cm^2-steradian. This value of the total ionization (i.e., the total intensity) is a factor of 50 lower than is obtained from one set of reported values[1] and there are even greater fluctuations than this in other electron intensity measurements. These fluctuations are correlated with solar activity, and are not resolvable when it comes to calculating the operating lifetimes of solar cells in the electron belt.

III. DESCRIPTION OF SOLAR CELLS

The "standard" silicon solar cells that have been used in most applications to date are 1 × 2 cms in surface area, roughly .020" thick. The base region is arsenic-doped n-type, and the surface layer is boron-doped p-type, roughly one micron thick. As a result of recent findings that under some conditions n/p cells are significantly more radiation resistant than p/n cells several manufacturers have developed n/p cells having nearly as high initial efficiency as the conventional p/n. The base materials in these cells is boron-doped, and the surface is phosphorus doped n-type.

During the course of the present study a large number of p/n cells manufactured by Hoffman Semiconductor Corp. and International Rectifier Corp., and n/p cells made by USASRDL, RCA Laboratories, and by RCA-Lancaster were irradiated. These cells had conversion efficiencies varying from 5 to 14% (measured under artificial illumination) with a variety of surface treatments. Some had single strip contacts along the long side of the surface; some had thin conducting grids on the surface to reduce the series resistance of the surface layer; some had anti-reflection coatings (a thin boro-silicate glass may be formed during the boron surface diffusion for example) and some were bare.

IV. PREVIOUS RESULTS

When the present study was undertaken there was some data available on radiation damage to silicon cells by electron, gamma, proton, neutron, deuteron, and alpha particle irradiation, all at widely scattered energies.

Using 1.7 Mev electrons Loferski and Rappaport found that 5×10^{13} electrons/cm^2 were required for a 25% loss in conversion efficiency.(6) Electron damage to bulk silicon has been studied by a number of workers.(7-18) From the behavior of resistivity and mobility as a function of temperature during bombardment a number of defect levels in the energy gap have been located, as shown in Fig. 2.(18) The level at 0.3 ev above the valence band has been attributed by Wertheim to be the principal recombination center for holes in n-type silicon; he has reported the cross section being between 2.8×10^{-14}(7) and 8×10^{-13} cm^2.(19) The level 0.16 ev below the conduction band is generally held responsible for recombination of electrons in p-type silicon, the cross section being 2×10^{-15} cm^2 according to Wertheim.(19) The difference in cross section may explain the difference between the p/n and n/p cell damage rates, but threshold damage measurements made recently do not confirm this in detail.

The majority carrier removal properties of these levels are not as important in the photovoltaic effect as the minority carrier recombination and will not be discussed in this report.

In addition to measurements of resistivity, mobility and lifetime work has been done on the infrared absorption and photoconductivity in irradiated silicon. This has shown the the existence of absorption bands associated with transitions involving the levels shown in Fig. 2 and other levels which are not of importance to the photovoltaic effect.(13)

Proton bombardment of solar cells by Loferski and Rappaport at an energy of 17.6 Mev showed that 3.5×10^{10} protons/cm^2 produced a 25% loss in efficiency.(6) Details of the position and capture cross sections of the levels produced by proton bombardment have not been measured to date.

The effect of gamma irradiation has been studied by Enslow and Junga[20] using cobalt-60 as a source of 1.25 Mev average energy gammas. They found that a total dosage of 8.8×10^7 ergs per gram was required for a 25% loss of photovoltaic conversion efficiency (this is the equivalent of $10^6 r$).

Although photoelectric effect and pair production are both possible the principal interaction is the production of compton electrons, having energies from zero to approx. 1.03 Mev, the average energy being $\approx$ 0.6 Mev. From the dosage figure given above it is relatively easy to calculate the number of electrons crossing a 1-cm^2 cross section of the cell; it is 1.0×10^{13} electrons/cm^2. Since these will have the characteristic compton energy spectrum, many will be low in energy and will produce little damage. A basis for calculating the average damage produced by such a distribution is provided by the curves given in Fig. 3 which show ϕ_c vs. E for electrons. Using the expression:

$$\langle \phi_c^{-1} \rangle = \int_0^{E_{max}} \phi_c^{-1} \, P_c(E) \, dE \qquad (1)$$

where $P_c(E)$ is the energy distribution of the compton electrons, one obtains $\langle \phi_c \rangle = 4.5 \times 10^{13}$ cm^{-2}.

Based on the monoenergetic electron work, therefore, one would predict a cobalt-60 gamma ray dosage (for 25% loss of efficiency) of 4×10^8 ergs/gram which is a factor of 4.5 higher than was measured by Enslow and Junga. In view of the difficulties of measuring gamma dosage and also the large fluctuations ϕ_c with initial cell efficiency, for example, this difference does not seem excessive.

Neutron damage has been studied far more extensively than either proton or electron damage, but there is very little sound basis at present for applying the results to either of the latter cases. Based on a comparison of the elastic neutron scattering cross section with the proton elastic cross section (including coulomb and nuclear scattering) one would expect that at 10-20 Mev there would be very little difference in the total number of lattice displacements. Although there is little reason to question the accuracy of the calculations the experimental facts are that protons in this energy range are much more damaging than neutrons. A comparison of electron, proton, and neutron damage rates will be given in Section VII.

V. DESCRIPTION OF THE IRRADIATION FACILITIES USED IN THE STUDY

Electron Irradiations were made entirely here at RCA Laboratories using the 1-Mev Van-de-Graaff generator. Proton bombardment was carried out using the facilities of High Voltage Engineering Corp in Burlington, Mass. (proton energies of 0.6, 1.0 and 1.5 Mev) using the small cyclotron at Brookhaven National Laboratory (8.3 Mev) and the Princeton University Cyclotron (19 Mev).

A schematic drawing of the experimental arrangement is shown in Fig. 4. The samples being irradiated were mounted at an angle of 45° to the incident beam in order to permit continuous monitoring of the photovoltaic response of the cells throughout irradiations. For the electron and the low energy proton irradiations the beam current was measured from the faraday cup shown in the figure. This was perfectly satisfactory for the electron runs, but the low beam intensities required for the proton runs made the current reading quite difficult, and this represents a major source of the final uncertainty in the low energy proton data. It was possible at the higher proton energies to interpose a thin ionization chamber in the beam just before the sample; by providing current amplification of about 10^3 it was possible to make more accurate measurements of the beam currents in these runs.

VI. THEORY

The process of recombination of excess carriers in a semiconductor occurs principally through intermediate states in the forbidden gap; direct recombination, by comparison is highly forbidden in silicon. A theory of the recombination process has been given by Shockley and Read[21] and by Hall.[22] Exact solutions of the problem exist only under fairly restricted conditions which limit the concentrations of injected carriers and the density of trapping levels in the gap. An understanding of the damage process involves at least knowing the introduction rates, recombination cross-sections and energy levels of the radiation-induced defects, most of which can be deduced from the effect of irradiation on the minority carrier lifetime *vs* temperature. There are numerous methods for measuring the lifetime of excess carriers, involving different means of injecting or observing the carriers.

An important result of the theory in References (21-22) and of a treatment of the transient recombination process by Wertheim[23] is that the excess carrier lifetimes measured by different methods may be quite different, depending on the injection level, or on whether one is observing equilibrium or transient recombination, and depending on the concentration of recombination centers. In the case of small injection levels the transient recombination lifetime goes according to

$$\frac{1}{\tau} = \frac{1}{\tau_{\text{initial}}} + \lambda\phi \qquad (2)$$

in the early stages of bombardment. In the light bombardment case the relationship between the diffusion length determined from equilibrium recombination measurements and the transient recombination lifetime is the familiar

$$L^2 = D\tau \qquad (3)$$

That is to say, the lifetimes determined for equilibrium and transient recombination conditions are the same. In the case of high concentrations of recombination centers, however, this is not generally true.[19] Furthermore, if as in the case of radiation-induced defects in silicon, where there is probably more than one recombination level, the reciprocal lifetimes will not necessarily add linearly, and Eq. 2 will not be valid.

This illustrates some of the reservations that must be made in considering the results of any specific lifetime or diffusion length measurement in normal and irradiated silicon. There can readily be large discrepancies between lifetimes measured under different injection conditions or recombination center concentrations.

Spectral Response of Photovoltaic Cell – A theoretical treatment of the spectral response of silicon photovoltaic cells in which both base and surface layer response was taken into account has been made by Loferski and Wysocki[24] and by Dale.[25] The results of their calculations were discussed at some length in the previous quarterly report, and will only be summarized here.

If $a = a(\lambda)$ = absorption coefficient of silicon

L_B = diffusion length of minority carriers in the base

$L_S = \frac{1}{\nu}$ = diffusion length of minority carriers in surface layer

ℓ = junction depth

the expressions obtained for the base and surface response are

$$Q_B = \frac{a L_B e^{-a\ell}}{(1 + a L_B)} \qquad (4)$$

$$Q_s = \frac{1}{\alpha(1 - \nu^2/\alpha^2)} \left(\frac{2\alpha e^{+\alpha \ell} - 2\nu e^{\nu \ell} + (\nu - \alpha)e^{-\nu \ell}}{e^{\nu \ell} - e^{-\nu \ell}} \right) e^{-\alpha \ell} \quad (5)$$

The characteristic shapes of these two expressions are shown in Fig. 5. The base response has a maximum at

$$\alpha_m = \frac{1}{2L_B}\left[\sqrt{1 + \frac{4L_B}{\ell}} - 1\right] \quad (6)$$

and is reasonably symmetric in shape, whereas the surface response drops off only very slightly at extremely high-α. From a detailed analysis of the spectral response of a solar cell using Eqs. (4)-(6) it is possible to determine ℓ, L_B, and L_S.

In the case where a single recombination level is introduced, the concentration of said levels is low, and for low injection levels, the constant λ in Eq. (2) is given by

$$\lambda = n_r \sigma_r v_t \quad (7)$$

where n_r is the number of centers per unit length of traversal of the material by the bombarding particle, σ_r is the recombination cross section per defect, and v_t is the thermal velocity of the minority carriers. Under somewhat more stringent limitations an expression analogous to (7) may be obtained for the case of more than one recombination center:

$$\lambda = \sum_i n_{ri} \sigma_{ri} v_t \quad (7)$$

It is convenient to calculate explicitly from Eq. (2) to (7) the variation of short circuit current flowing from the base of a cell across the junction with total bombarding flux under various types of illumination. Under monochromatic light of long wavelength (deeply penetrating radiation)

$$\frac{I_{so}^2}{I_s^2} - 1 = \lambda r_o \phi \qquad (\alpha \text{ small}) \quad (8)$$

At short wavelengths (strongly absorbed radiation)

$$\left[\frac{I_{so}}{I_s} - 1\right]^2 = \frac{\lambda r_o \phi}{(L_o \alpha)^2} \qquad (\alpha \text{ large}) \quad (9)$$

where I_{so} is the preirradiation value of I_s, ϕ is the flux and τ_o is the preirradiation lifetime under equilibrium conditions. These two equations indicate the large difference between the damage rates under the two types of illumination.

It is convenient in analyzing the spectral damage characteristics to define the fractional loss of response at a given wavelength:

$$\Delta = 1 - \frac{I_s}{I_{so}} \quad . \tag{10}$$

Equations (8) and (9) may be rewritten in terms of Δ:

$$\frac{1 - \Delta}{\Delta} = \frac{1}{(1 + \lambda \tau_o \phi)^{1/2} - 1} \qquad (\alpha \text{ small}) \quad (11)$$

and

$$\frac{1 - \Delta}{\Delta} = \frac{L_o \alpha}{(\lambda \tau_o \phi)^{1/2}} \qquad (\alpha \text{ large}) \quad (12)$$

The analysis of damage to the photovoltaic response is based on Eqs. (2) through (12). From the spectral response measured before irradiation the values of ℓ and L_B can always be determined. In some cases where the surface layer response is well-defined it is also possible to determine L_S. From the ratios of the spectral response before and after irradiation using Eqs. (11) and (12) the base diffusion length before and after irradiation and λ can be determined. An independent determination of λ can be made by directly measuring the lifetimes throughout irradiation, and using Eq. (5).

This provides several independent measurements of quantities which are of fundamental importance in the performance of a photovoltaic cell. The factor λ has a clear physical significance given by Eq. (7). If, indeed, λ and the spectral response are known for a given cell then it is simple and straightforward to calculate the spectral response and the photovoltaic current under any specified illumination (artificial or solar) after any given bombarding flux.

It is suggested, therefore, that the quantity λ provides a much more *useful* and *significant* parameter specifying the damage susceptibility of a given cell than the conventional but unmeaningful ϕ_c, that is now almost universally used. An important advantage that accrues from the suggested choice of λ is the elimination of the initial cell efficiency from the damage susceptibility. It is true that low-efficiency cells suffer proportionately less damage for a given flux than ones of high efficiency, but this clearly does not make them preferable to better cells. The apparent constancy of λ and the validity of the model of the performance of a solar cell developed under the present contract make it possible to calculate the degradation of the behavior of a cell under any radiation flux and under any given illumination once its relative spectral response and the single parameter λ are known, regardless of its initial efficiency.

This is a purely phenomenological approach, and the fundamental problems which have thwarted an understanding of the damage process in silicon solar cells still remain. There exist quite large fluctuations in damage susceptibility among cells which are apparently identical in their initial electrical and physical properties, and these fluctuations cannot be eliminated by the approach that is suggested here. Until a better basic understanding of the damage processes is achieved the fluctuations will simply be embodied in the parameter λ.

VII. EXPERIMENTAL RESULTS

A. CHANGES IN ELECTRICAL PROPERTIES OF PROTON IRRADIATED CELLS

The first proton irradiations that were carried out under the present contract were made at High Voltage Engineering Co., in Burlington Mass. A beam of 0.6, 1.0 and 1.5 Mev protons was provided by a 2-Mev positive-ion Van de Graaff generator. The initial and final conversion efficiencies and the i-V characteristics under approximately 100 milliwatts/cm^2 of artificial illumination were measured throughout the runs. The results are summarized in Table I below.

TABLE I

POLARITY	ϕ_c		
	0.6 Mev	1.0 Mev	1.5 Mev
p/n	4.7×10^{10}	1.3×10^{10}	$1\text{-}1.5 \times 10^{10}$
n/p	7.6×10^{11}		2.9×10^{11}

The major experimental difficulty in these runs was in measuring the low beam currents required to keep the damage from occurring prohibitively quickly (10^{-10} amp. typically). At higher energies it was possible to pass the beam through a short ionization chamber before striking the target; the ionization current was upwards of 10^3 greater than the proton current, and its measurement was simple and convenient. At these energies, however, the use of an ionization chamber was impossible, and the current had to be measured directly by interrupting the bombardment. As a result there is some uncertainty in the results on this account, but in view of the large fluctuations from cell to cell what were found in all of the proton bombardments this uncertainty is not considered serious.

The Brookhaven 60" cyclotron provided a beam of protons whose mean energy after passing through a short helium-filled ionization chamber was 8.3 Mev. The experimental arrangement for these runs was similar to that used in the low energy proton runs; an exception was that in addition to the electrical measurements that were described above, the spectral response before and after irradiation was measured for several of the cells that were irradiated. The results at this energy are summarized in Table II.

TABLE II

CELL #	POLARITY	MANUF.	INITIAL EFF.	ϕ_c ($\times 10^{-10}$) PROTONS/CM^2	λ	L_{B_o}	L_B	ℓ
6	p/n	Hoffman	10%	1.3				
12	↓		10	11.0				
15			12	5.3				
38			9.5	2.6	12×10^{-5}	93μ	7μ	.6μ
39			12	12.0				
42		I.R.C.	10.5	2.2	12	100	7	.8
44			10	4.3				
45			11	1.6				
46			11	2.0	18	144	7.4	.8
47			11	6.9				
51			11	5.8	6.9	126	7.5	.9
60	n/p	USASRDL	6.4	9.6	3	48	13	.9
61	↓		7.8	8.5	6.8	48	13	.9
62			5.6	7.0	1.5	200	10	.9
Average of p/n cells				5.0 ± 3.7	12.2 ± 4.5			
Average of n/p cells				8.4 ± 1.0	3.8 ± 2.7			

The values of ϕ_c were computed from the i-V curves under artificial illumination. Under solar illumination ϕ_c is expected to be slightly higher. The values of λ were computed from the spectral responses measured before and after irradiation. Clearly, substituting λ for ϕ_c does not in any way reduce the size of the fluctuations in the results.

Two important results follow from the spectral response analysis, aside from a determination of λ. The photovoltaic response is *predominantly* in the base region of the cell in all cells studied, and a great many cells have response *exclusively* in the base. It also follows that in all cells the predominance of the damage to the photovoltaic response occurs in the base.

These results are illustrated in Fig. 6 which shows the spectral response of a cell having a high relative surface-layer response. The solid curves are the total response; the dashed curves are the base and surface response making up the solid curves, calculated from Eqs. (2) and (3). Figure 7 shows the spectral response of the majority of cells having very little surface response. Both Figs. 6 and 7 show the response before and after irradiation illustrating the second statement above, the damage to the photovoltaic response occurs mainly in the base region.

A number of cells were bombarded with 19 Mev protons using the Princeton University cyclotron. As in the 8.3 Mev runs the beam passed through a helium-filled ionization chamber before striking the target. In addition to the measurements that were made in the lower-energy proton runs the minority carrier lifetimes were monitored throughout the 19 Mev irradiations using pulse injection. Together with the spectral response analysis this provides two independent determinations of the values of L_B and λ.

The results of the lifetime measurements on 8 of the cells that were bombarded at 19 Mev are shown in Figs. 8 and 9. Most of the cells exhibited a linear dependence of $1/\tau$ on ϕ, but several of the n on p cells which were made by RCA-Lancaster showed strong saturation effects at large fluxes. The decay of the short-circuit current for the same 8 cells is shown in Figs. 10 and 11. The results are summarized in Table III.

There is rather poor correlation between the individual values of λ determined from the lifetime measurements and from the spectral response analysis, and there is about a factor of 6 difference in the average. This discrepancy is beyond the limits of experimental error for most of the cells that were analyzed. One possible explanation lies in the experimental method by which the lifetimes were measured. The pulse injection method is convenient and simple, but is subject to surface recombination effects. It is quite possible that the injection-extraction lifetime is completely limited by surface recombination, and if this is the case the slope of $1/\tau$ vs ϕ is characteristic of the introduction rate for surface rather than bulk recombination centers. Another possible reason for the discrepancy is the difference between equilibrium and transient lifetimes that was mentioned in the previous section.

TABLE III

19 Mev PROTON RESULTS

CELL NO.	POLARITY	ϕ_c (PROTONS/cm^2)	λ FROM $1/\tau$ vs ϕ	FROM SPECTRAL RESPONSE λ	L_{B_o}	L_B
14	p/n	2.7×10^{10}	2.6×10^{-5}	1.2×10^{-4}	120μ	5μ
25	↓	1.1	2.5	2.1	170	4
48		1.4	2.4	1.0	130	5.5
50		3.5	[.25	6.2	420	≈ 2]*
24		0.85	2.5			
74				0.8	65	12
86		1.0	3.6	4.0	110	5
87		1.3	4.4	4.4	95	7
88		1.0	5.5			
89		1.0	4.9			
90		0.45	3.5	[11.0	120	≈ 1.5]*
91		0.25	12	4.5	130	5
93		0.7	8.0			
98		1.4	1.4	1.3	95	3
105		5.4	0.6			
140	n/p	6.0	0.67	.42	105	10
142	↓	5.8	2.0	.24	145	22
143		5.0	1.6			
144		5.0	1.3			
Average	p/n	1.9(±1.7)	4.2(±2.9)*	2.4(±1.6)*		
Average	n/p	5.5(±0.2)	1.4(±0.5)	0.3(±0.1)		

*The final values of L_B are not accurately determined for these two cells, and the values of λ were not included in computing the average.

Although there are large fluctuations in the results for any given group of cells the results are sufficiently good to allow a calculation of the operating lifetime of an average cell in the Van Allen proton belt, provided the cell is protected from the low energy end of the proton spectrum by a suitable cover. The fluctuations and the systematic variation with energy of the damage rates are both small compared with the variations with energy of the proton intensity and as a consequence the value of ϕ_c may be taken to be approximately independent of energy. The conditions under which a calculation may be made and the specific result of such a calculation will be discussed in Section VIII.

B. CHANGES IN THE ELECTRICAL PROPERTIES OF ELECTRON-IRRADIATED CELLS

At the outset of the present study there was in existence a considerable amount of experimental data on damage to the electron-voltaic response of silicon cells, particularly in the energy region near the displacement threshold. An effort was made during the course of the present investigation to connect this data with damage to the photovoltaic response of similar cells. The results which were described in the previous report are shown in Fig. 3. The right-hand scale in this figure gives the flux scale for the electron-voltaic damage; the photovoltaic damage points are plotted according to the flux scale on the left side of the figures. There is a uniform scale difference of a factor of 300, which is consistent with what one would expect on the basis of Eq. (8) and (9).

It is possible to calculate an average operating lifetime for a solar cell in the outer (electron) Van Allen belt using Fig. 3 in a manner analogous to that used in computing the effect of the cobalt-60 compton electron spectrum. This will be considered in the next section.

Values of λ were obtained for a group of four p/n cells bombarded with 250 kev electrons, and for one n/p cell bombarded at 500 kev. From Fig. 3 one would expect that the values of λ for these two cases would be approximately equal (ϕ_c being nearly the same). The value of λ was obtained for the 250 kev, p/n cell group from an analysis of the spectral responses before and after irradiation; in the 500 kev, n/p case λ was calculated from the behavior of the electron-voltaic response as a function of total electron flux. The values of λ in the two cases were 1.0×10^{-9} and 0.67×10^{-9} respectively, in satisfactory agreement.

Lifetime measurements were attempted during the low energy electron runs; it was reported briefly in the previous report that this was thwarted by changes in the surface properties of the cells which occurred at very low fluxes, and for bombarding energies well below the displacement threshold. Using the pulse injection method, these changes resulted in a rapid decrease in the apparent lifetime. The "lifetime" recovered slowly in vacuum, reaching its original value after roughly 12 hours in a vacuum of 10^{-5} mm Hg. When the process was repeated and the cell was exposed to air, recorvery occurred in a few minutes. A cell that was exposed to dry nitrogen after irradiation recovered at a rate comparable to that in vacuum.

The lifetime changes were not accompanied by any change in the photovoltaic short-circuit current, but it has recently been observed that small changes in the open-circuit photovoltage can occur.

Since the effect of surface states in the pulse-injection method may have an important bearing on all of the lifetime measurements that were made using this technique a group of cells were bombarded at various sub-threshold energies to study the induced changes. One possible mechanism that was suggested was that the creation of surface states would result in an inversion layer being formed on the side edges of the cell. The result would be that part of the effective junction would lie in a region of much higher doping, and hence injection would occur predominantly in a region of very short lifetime.

To test this and other possibilities, the cells were bombarded using two different masks. In one case the entire cell (surface, contact, and sides) was exposed. In the other case only a small area of the surface, removed from the contact and the edges, was exposed to the beam. The result was only a slight reduction in the magnitude of the changes when the small mask was used. This rules out the contact and the side edges, and suggests states in the surface layer. The nature of these states and the extent to which they are generated during the proton bombardment remain unanswered at present. The values of λ obtained from the spectral response analysis, therefore, should be regarded as more reliable than those obtained from the injection measurements.

It may be noted in passing that surface effects have previously been observed by Spear[27] in low energy electron bombardment of germanium.

C. ALPHA PARTICLE DAMAGE

Two cells were irradiated with 33 Mev alpha particles using the Brookhaven cyclotron; one cell was p/n and the other was n/p. Preliminary results, given in an eariler report, indicated considerably higher damage rates than were observed in the 8-Mev and 19-Mev proton bombardments, and a difference of roughly a factor of five between the p/n and n/p cell.

The spectral response of these two cells has been analyzed, and the results are summarized in Table IV.

TABLE IV

CELL NO.	POLARITY	INITIAL EFFICIENCY	ϕ_c	L_{B_o}	L_B	ℓ	λ
41	p/n	11%	2.1×10^9	58μ	6.2μ	$.9\mu$	6×10^{-5}
66	n/p	6.5%	1.0×10^{10}	400μ	12μ	1.1μ	7.7×10^{-5}

Although ϕ_c differs by a factor of five for the two cells, the values of λ are nearly equal. Since cell 66 was low in initial efficiency, and had consequently a smaller relative loss of efficiency during the early stages of bombardment, the results are consistent with the damage rates being equal in the two cases, as indicated by the similar values of λ.

D. A COMPARISON OF ELECTRON, PROTON AND NEUTRON DAMAGE RATES

In order to make a comparison of the experimental data on electron, proton and neutron damage the number of displacement-producing collisions and the total number of primary and subsequent displacements was calculated for the following:

ELECTRONS at 750 kilovolts
PROTONS at 17 Mev
NEUTRONS at 17 Mev

The displacement energy for silicon was taken to be approximately 15 ev, and electron bombardment was assumed to produce only single displacements. The latter assumption may be slightly in error, since the maximum energy transfer in a head-on collision between an electron at this energy and a silicon atom is 100 ev, but such an error will be unimportant for the present calculations.

The total elastic cross section for 17 Mev protons on silicon was estimated from the data of Dayton and Schrank on proton scattering by aluminum;[28] both coulomb and nuclear forces are included.

The neutron cross section at 17 Mev is assumed to be isotropic, with a total cross section of 2 barns. The assumption of isotropy is not a particularly good one, according to the data of Walt and Barschall[29] but the error introduced on this point is not serious.

The results of the calculations are summarized in Table V

TABLE V

PARTICLE	ENERGY	θ_{min}	n_c	n_d	λ	
					n-type	p-type
Electrons	750 kev	46°	0.65	0.65	1.6×10^{-7}	10^{-8}
Protons	17 Mev	0.21°	185	$1\text{-}2 \times 10^3$	10^{-4}	2×10^{-5}
Neutrons	17 Mev	0.21°	0.1	$2\text{-}4 \times 10^3$	10^{-6}(30)	4.4×10^{-7}(30)
					$[3 \times 10^{-7}]$(32)	

θ_{min} = the minimum scattering angle for which the recoiling silicon atom possesses sufficient energy to be displaced

n_c = the number of collisions per centimeter of traversal of the crystal for which $\theta \geq \theta_{min}$

n_d = the total number of displaced silicon atoms per centimeter of traversal of the crystal, including both primary and all succeeding displacement processes.

The interesting feature of these results lies in the similarity of the electron and proton values, and in the difference between these and the neutron values. The values of λ for electrons and protons are very nearly proportional to n_d, the total number of displacements, whereas if electrons and protons are compared with neutrons the values of λ are more nearly proportional to n_c, the total number of collisions than to n_d. Since the total number of lattice displacements per centimeter is nearly the same for neutrons and for protons, this suggests that the electrical damage resulting from the high density displacement spikes occurring in neutron-irradiated silicon is far less than that produced by the same number of individually displaceu atoms produced over larger distances in proton-irradiated silicon.

E. PROTON BOMBARDMENT OF SAPPHIRE AND PYREX

Following reports from Bell Telephone Laboratories, that sapphire was unusually resistant to radiation discoloration compared with any of the glasses a window .040" thick was mounted in front of a solar cell and bombarded with 19 Mev protons. The sapphire window was considerably thicker than the proton range so no damage to the cell was possible.

After a total flux of 3×10^{12} protons/cm^2 there was no detectable loss in the output of the solar cell. From this it is concluded that at least 3×10^{13} protons/cm^2 would be required for 25% loss of transmission in the spectral range to which the cell is sensitive. This result is consistent with the measurements of Arnold and Compton(26) in which the only appreciable optical absorption band was introduced at $\lambda = 2050$ Å after electron fluxes larger by a factor of ≈ 100 than would be required to cause 25% loss of response to an uncovered cell.

A pyrex microscope slide, on the other hand, became severely discolored after only 5×10^{11} protons/cm^2.

Figure 12 shows a microscope slide that was bombarded with 10^{12} protons/cm^2. The ink markups show the outline of the cell mounted behind the slide. This particular slide was irradiated in order to check the uniformity of the proton flux over the surface of the cell, but it serves to illustrate the severe browning that occurs in ordinary glass at low proton fluxes.

F. ULTRAVIOLET IRRADIATION

The ultraviolet exposure of solar cells and cover materials that was described previously has been continued. The lamp being used for this work provides roughly five times the integrated upper atmosphere intensity over the wavelength region from 2200 to 3000 angstroms. Four cells (two p/n and two n/p) were exposed for a total of 1860 hours, which was the equivalent of over a year of upper atmosphere solar illumination. There was no observable deterioration in the short circuit current of the cells; the open circuit voltages for all four cells dropped slightly (from 3 to 5%) .

Specimens of quartz and sapphire were also exposed; after 500 hours there was no significant discoloration of either material. By comparison, ordinary glasses became perceptibly brown after such exposures.

The most serious damage in the cell cover materials that are commonly considered occurs in the transparent epoxy cements that are used to make optical (and thermal) contact between the glass (or quartz or sapphire) cover proper and the surface of the cell. Figure 13 shows the measured transmission of a sapphire plate that was irradiated from the front surface and had a layer of epoxy on the rear surface. (The epoxy was CIBA 502, with HM 951 hardener). There was a clear increase in the uv absorption after 66 hours, and after 741 hours there was strong absorption at 1 micron as well.

G. ELECTRON SPIN RESONANCE

One of the most promising tool for studying the nature of radiation damage is electron spin resonance (ESR). Accordingly some work was started under the present contract using this technique. This preliminary effort did not progress to the point where useful information on the nature of radiation defects was obtained. However some information important for further study of this problem resulted and since we expect to devote considerable effort to the spin resonance technique in the future a brief discussion of the problem is given here.

There are two main experimental difficulties when the ESR technique is applied to the radiation damage problem. One is that high sensitivity is required to observe by spin resonance. The number of observable defects is limited[14] by the requirement that an elec- from the donor atom (for n-type material) must attach itself to the defect side before a spin resonance signal can be obtained. Since the defect sites will normally lie below the donor atom in the forbidden gap this will occur for example when the temperature is lowered sufficiently. Consequently the spin resonance experiments are usually performed at liquid nitrogen or lower temperatures. The absorption of microwave power by the free carriers in the silicon sample can also be a problem and may necessitate going to liquid hydrogen or liquid helium temperatures. The number of defect sites with electrons can not exceed the number of donor atoms and so for 1 Ω-cm silicon, the number of observable defects is approximately 5×10^{15}/cc.

The second difficulty is the long spin-lattice relaxation times associated with radiation damage sites, where relaxation times of several minutes or longer are normal. This means that a very small amount of microwave power will saturate the resonance lines. This in turn affects the sensitivity that can be obtained and in practice requires that the resonance lines be studied in the dispersion mode which does not show the same saturation behavior as the absorption mode.

The equipment used was a Varian 4500 EPR spectrometer, a Varian 4545 Liquid Helium Accessary and a Harvey-Wells 12" rotatable electromagnet. The sensitivity of the apparatus was calibrated using a ruby sample which contained 7×10^{16} Cr^{3+} ions. The minimum detectable number of spins for a signal to noise ratio of unity was

$$N_{\min} = 2 \times 10^{12}\,\Delta H \text{ spins for } S = 1/2$$

where ΔH = width of resonance line

This number holds for room temperature using the absorption mode of the microwave bridge and is 5 times higher (less sensitive) than the figure claimed by the manufacturer.

Before irradiation it is possible to observe the ESR from the donor atoms in silicon, in this case the arsenic atoms. Eight unirradiated silicon solar cells with the junction and metal backing removed were placed in the microwave cavity and the arsenic donor lines were observed in the despersion mode at liquid helium temperature. For this measurement,

Volume of Si sample	=	$0.7\ cm^3$
No. of As atoms/cm^3	=	6×10^{15}
Total No. of As atoms	=	4×10^{15}

The spectrum consists of four hyperfine lines about 10 gauss wide and spaced approximately 80 gauss apart. The signal to noise ratio was 13. A sample irradiated with a sufficiently high flux of electrons should indicate the presence of A-centers identified by Watkins and Corbett[14] with an intensity approximately equal to the arsenic lines observed before irradiation. Several irradiated samples were studied but no resonance signal corresponding to radiation defects was observed. The reason for this is believed to be that the number of defects in the samples studied was too small to be observed. The solar cells irradiated for study in this contract did not have sufficient defects produced to use all the donor electrons. However a solar cell was irradiated on the RCA Van de Graaff at $E = 800$ kev with $\phi = 10^{17}$ el/cm^2. For this sample we assume

No. of defects observable/cm^3	$= 6 \times 10^{15}$
Volume of sample	$= .05$ cm^3
Total No. of defects	$= 3 \times 10^{14}$

This is just on the edge of our present sensitivity and no signal was observed.

The result of this preliminary study suggests that for further work we must irradiate larger samples of silicon and further increase the sensitivity of the EPR spectrometer. Those steps will be undertaken when work on spin resonance of radiation damage sites is renewed.

H. A COMPARISON OF THE DAMAGE RATES UNDER ARTIFICAL LIGHT AND SUNLIGHT

In addition to determining a value of the damage parameter λ the spectral response analysis that was discussed briefly in an earlier section of this report (see Report No. 3 for a more detailed discussion) has a very useful side result. Since the damage rates exhibit a wavelength and flux dependence that is consistent with the theoretical model, it is possible to calculate the damage rates under any specified illumination if the initial spectral response and λ are known. (From the initial spectral response and λ the spectral response at any intermediate flux point can be computed, and knowing the illumination spectrum the loss of response follows directly.)

The loss in output has been calculated for a typical cell under two commonly used broad-spectrum light sources. The first is sunlight; the solar spectrum was taken from Johnson.[31] The second light source was a 2700°K to 3000°K black body. Cell No. 38 was considered to be typical; its spectral response before and after irradiation with 8.3 Mev protons which was shown in an earlier report[33] is characteristically base response.

The results of the calculation are shown inf Fig. 14 along with the experimental values of I_s which were measured using a tungsten lamp. There is an uncertainty in the normalization of the spectral response that is roughly ± 5%, and this may account for the fact that the measured current does not decay to as low a terminal value as was calculated for the black-body illumination. The experimental curve does not drop as steeply in the initial stages of irradiation as the theoretical curves, but otherwise the shapes are similar. Figure 15 which shows $(I_{so}^2 / I_s^2 - 1)$ vs ϕ illustrates the slow initial decay of the experimental curve compared with the theoretical curves, as well as the fact that at high fluxes all three curves tend to a slope of 1/2.

Comparing the artificial and solar spectrum decay rates, the loss of output current under artificial light is roughly 60% greater in the initial stages of bombardment than under the Johnson spectrum. In the extreme final stages of bombardment this difference would naturally disappear, but even after sufficient bombardment to lower the response under artificial light by one half there is still 47% more loss under artifical than under solar illumination.

VIII. OPERATING LIFETIME OF SILICON SOLAR CELLS IN VAN ALLEN BELTS

The data obtained in this contract on the degradation of a variety of types of solar cells under proton and electron bombardment can be used to estimate the lifetime of a solar battery operating in the Van Allen Belts. At first glance the large spread in ϕ_c for similar cells would indicate a rather large uncertainty in predicted lifetime. In practice however, a large number of solar cells will be operated in parallel and a predicted lifetime based on a statistical average of a large number of irradiated solar cells should be quite reliable. In this section the solar cell data will be analyzed so that solar cell lifetime estimates for different types of cells can be made.

A convient method of representing the average solar cell behavior is in the form of I_s / I_{so} versus flux. Then the average short circuit current can be calculated for any given flux. The average open circuit voltage could also be plotted in similar fashion. The general shape of the I_s vs ϕ for all cells in a fairly rapid drop in I_s followed by a much slower decrease in I_s with flux. This latter part of the curve can be approximated reasonably well by a straight line. It is the straight line portion of the curve that is likely to be of use in computing solar cell lifetime, and we represent it by the equation

$$I_s/I_{so} = A - B\phi$$

The largest group of cells irradiated in this contract were proton bombarded p/n cells. The data shows there is no difference in solar cell damage rate from 2 to 20 Mev protons and so they will be considered together. For a group of 31 p/n cells the best fit for B is found to be $B = .08 \times 10^{-11}$ protons^{-1} cm^2. The spread in the value of B is quite small from cell to cell. However the spread in A is considerable. The average value of A is 0.70. A graph of the average I_s/I_{so} vs ϕ is shown in Fig. 16.

To get an idea of the expected error in using this curve we can compute $I_s(\phi = 10^{11}$ protons/cm$^2)/I_{so}$ for a number of subgroups of the total number of p/n cells.

(case i) 6 p/n cells nos., 42, 44, 45, 46, 47, 51 8.3 Mev protons

$$\frac{I_{s\phi}}{I_{so}} = 0.66$$ 6% higher than predicted value

(case ii) 5 p/n cells, nos., 6, 12, 15, 38, 39 8.3 Mev protons

$$\frac{I_{s\phi}}{I_{so}} = 0.69$$ 10% higher than predicted value

(case iii) 16 p/n cells 19 Mev protons

$$\frac{I_{s\phi}}{I_{so}} = 0.57$$ 9% lower than predicted value

(case iv) 4 p/n cells 2 Mev protons

$$\frac{I_{s\phi}}{I_{so}} = 0.60$$ 2% lower than predicted value

The maximum error for the examples considered is 10% of $I_{s\phi}/I_{so}$. In terms of flux this represents an uncertainty of about 80%. The corresponding data for other types of cells is shown in Table V and Fig. 16.

TABLE V

AVERAGE PARAMETERS USED FOR ESTIMATING SOLAR CELL LIFETIMES

CELL POLARITY	MANUF.	IRRADIATION PARTICLE	PARTICLE ENERGY	NO. OF CELLS USED USED FOR AVERAGE	A	B	RANGE WHERE STRAIGHT LINE APPROXIMATION CAN BE USED
p on n	Hoffman, I. R.C.	proton	2,8.3,20 Mev	31	0.70	$.08 \times 10^{-11}$	$\phi > 10^{11}$ proton/cm^2
n on p	Signal Corps.	proton	8.3 Mev	2	0.77	$.06 \times 10^{-11}$	"
n on p	RCA Lancaster	proton	19 Mev	4	0.74	$.03 \times 10^{-11}$	"
p on n	Hoffman, I. R.C.	electron	250 Mev	4	0.79	$.13 \times 10^{-16}$	$\phi > 5 \times 10^{15}$

It is possible at this point to construct a curve such as shown in Fig. 17 which gives the current *vs* time in the Van Allen proton belt for the average solar cell, provided a suitable cover is provided to eliminate the low energy end of the proton specturm. Below 8 Mev virtually nothing is known of the proton intensity; as the energy is decrease towards 8 Mev the intensity is observed to increase rapidly.[4] This circumstance makes it difficult to calculate even the order of magnitude of the operating lifetime for an uncovered cell; the lifetime given for an uncovered cell in Table VI and the time scale shown in Fig. 17 below are rough upper limits estimated on the assumption that the intensity flattens abruptly at 8 Mev and is constant down to zero proton energy.

In the case of the electron belt the intensity has been measured down to energies well below the displacement threshold. The chief uncertainty in determining the electron-damage limited operating lifetime is caused by the large fluctuations in the total electron intensity that have been reported (perhaps correlated with solar activity, though this point is uncertain). The integrated intensities reported in Refs. 1 and 5 are 10^{13} and 2×10^{11} ev/cm^2-sec-sterad respectively.

(i) Proton damage to a covered cell – The most promising cover material based on its resistance to discoloration is sapphire. A plate 0.030" thick will stop roughly 18 Mev protons. Combining the data of Refs. 2-4 an estimate of the total number of protons above 18 Mev at the peak of the proton belt can be made; it is ≈ 2000 per cm^2 sec. Based on this figure it would take 2100 hrs. to accumulate a total of 25% loss of solar cell conversion efficiency.

(ii) The operating lifetime in the electron belt has been calculated for the two intensities reported in Refs. 1 and 5. For an uncovered p/n cell using the lower flux of Ref. 5 the lifetime is 1.3 years. If the higher flux of Ref. 1 is used, the lifetime for an uncovered p/n cell is 9 days. For uncovered n/p cells the two corresponding lifetimes are 33 years and 8 months, respectively. Since most of the damage is produced by the electron spectrum below 3 Mev a cover such as the 0.030" sapphire described above would effectively render both p/n and n/p cells immune to electron damage.

A curve that is similar to Fig. 17 showing I_s/I_{so} vs time in the electron belt for uncovered p/n and n/p cells is shown in Fig. 18. The two time scales indicate the large difference in damage rates of the n/p cells and p/n cells when the shape of the electron spectrum is taken into account.

The lifetime calculations are summarized in Table VI.

TABLE VI

		LIFETIME
PROTON BELT, UNCOVERED CELL		< 35 hours
PROTON BELT, CELL COVERED WITH .010" SAPPHIRE		120 hours
PROTON BELT, .030" SAPPHIRE COVER		2100 hours
ELECTRON BELT,	UNCOVERED p/n CELL	9 days[1] to 1.3 years[5]
	UNCOVERED n/p CELL	8 months[1] to 33 years[5]
	COVERED p/n CELL	*Very Large*
	COVERED n/p CELL	

CONCLUSIONS

In the early stages of the work on this contract it was hoped that a universal *efficiency versus flux* curve could be constructed. This would be possible if the damage introduction rate were a constant depending only on the bulk properties of silicon and independent of particular solar cell variations. It was soon apparent that this was not possible. Furthermore the spread in ϕ_c is greater than can be explained on the basis of variations of individual solar cell parameters such as base and skin diffusion length and junction depth. The spread in λ makes this point clear since λ is a property only of the silicon and in principle does not depend on solar cell parameters. We are forced to conclude that the silicon used in solar cells is not uniform as far as radiation damage properties are concerned. The variation in λ is the only evidence we have for this assumption but it is a strong one since much data has been taken and the spread in λ is well outside experimental error. They only explanation that can be advanced at this time is that the silicon in "similar" solar cells contains varying amounts of impurities which are effective in creating damage centers. This is not an unreasonable assumption but the experimental techniques used in this contract work, although very sensitive indicators of damage, do not allow a detailed investigation of the nature of the defects produced. Another possibility which can be considered is that the damage introduction rate is different at low flux and high fluxes in which case our λ's would be some sort of average over the flux range covered. The pulse injection lifetime measurements indicate a single damage introduction rate. However as explained earlier the interpretation of this experiment is somewhat doubtful. The other methods used to obtain λ, such as analysis of spectral response curves, depend only on measurements made before and after irradiation.

Based on the data that is now available on solar cell damage characteristics it is possible to compute the approximate life of a solar battery that is operated in either an electron or proton environment. In the specific background presented by the Van Allen belts there remain considerable uncertainties in the predictions, based largely on uncertainties in the particle fluxes, but to a lesser degree there remain uncertainties in the damage rates under exactly known fluxes. The remaining problems in this area are fundamental in nature. The nature and electrical properties of the radiation defects are to a great extent unknown. The recent work on spin resonance in neutron and electron irradiated silicon has helped somewhat, but only one or two of the numerous defects produced in silicon are understood at present. The ultimate solution to the problem of radiation damage in silicon solar cells will probably be achieved only after a more exhaustive attack on the fundamental nature of the defects.

It is evident from what is now known that an uncovered cell that is being operated at the intensity peak in either the proton or electron belt will deteriorate in a very short time. In the proton belt the evidence indicates that n/p cells will operate for roughly two to three as long as p/n cells on the average. The advantages of covering the cell are great (in terms of increased radiation resistance) and n/p cells retain the factor of two to three advantage over p/n cells. In the electron belt there is a far greater difference between p/n and n/p cell lifetimes. This is the result of the shape of the electron energy spectrum and the large differences in damage rates near threshold. An uncovered n/p cell, specifically, will operate above any given efficiency level for roughly 25 to 30 times as long as a p/n cell. In the electron belt even more than in the proton belt the operating lifetime is extended by suitably covering the cell.

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33. Quarterly Report No. 2 (present contract) Figure 16.

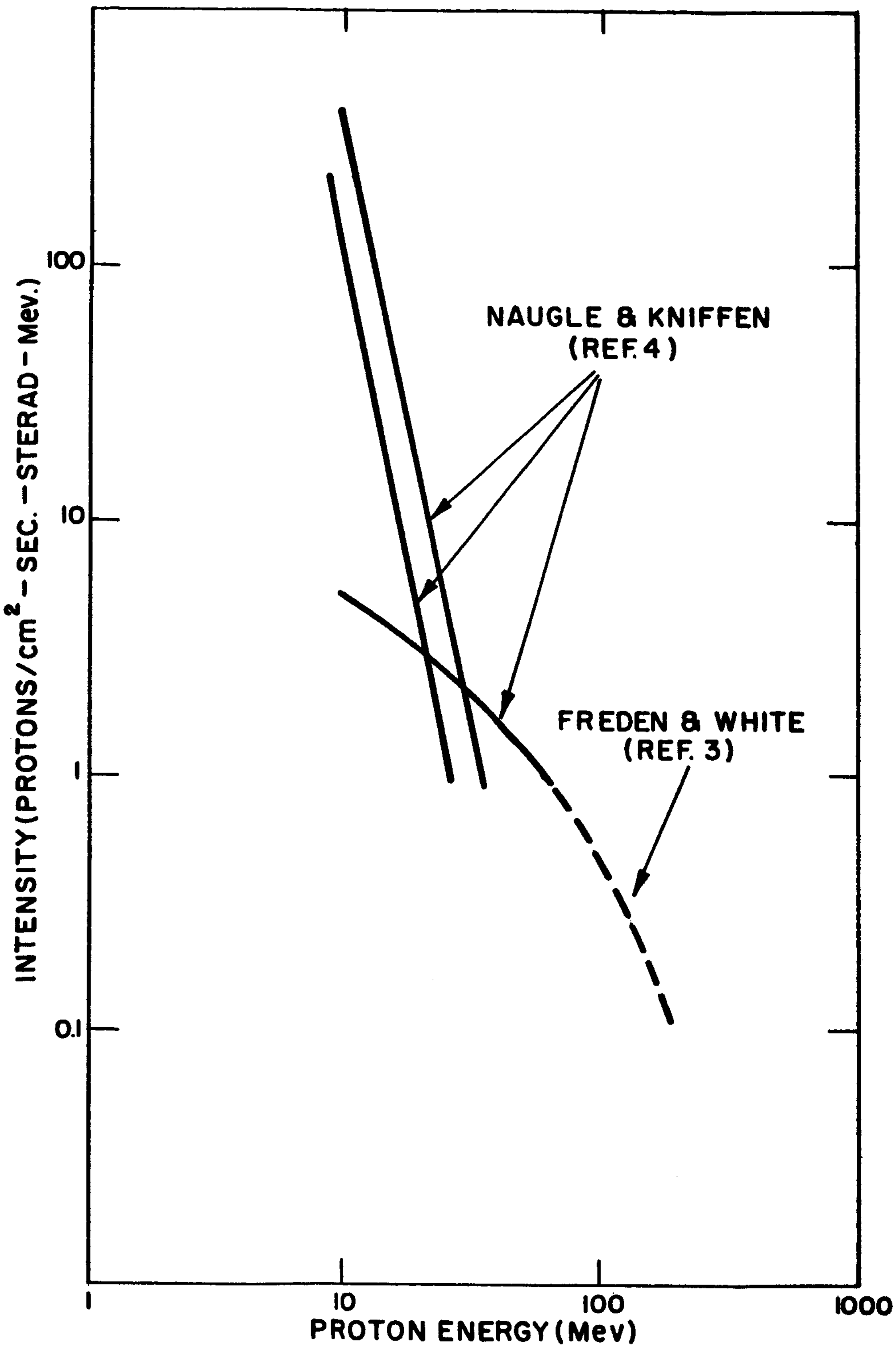

FIG. 1 DIFFERENTIAL ENERGY SPECTRUM OF PROTONS IN VAN ALLEN BELT

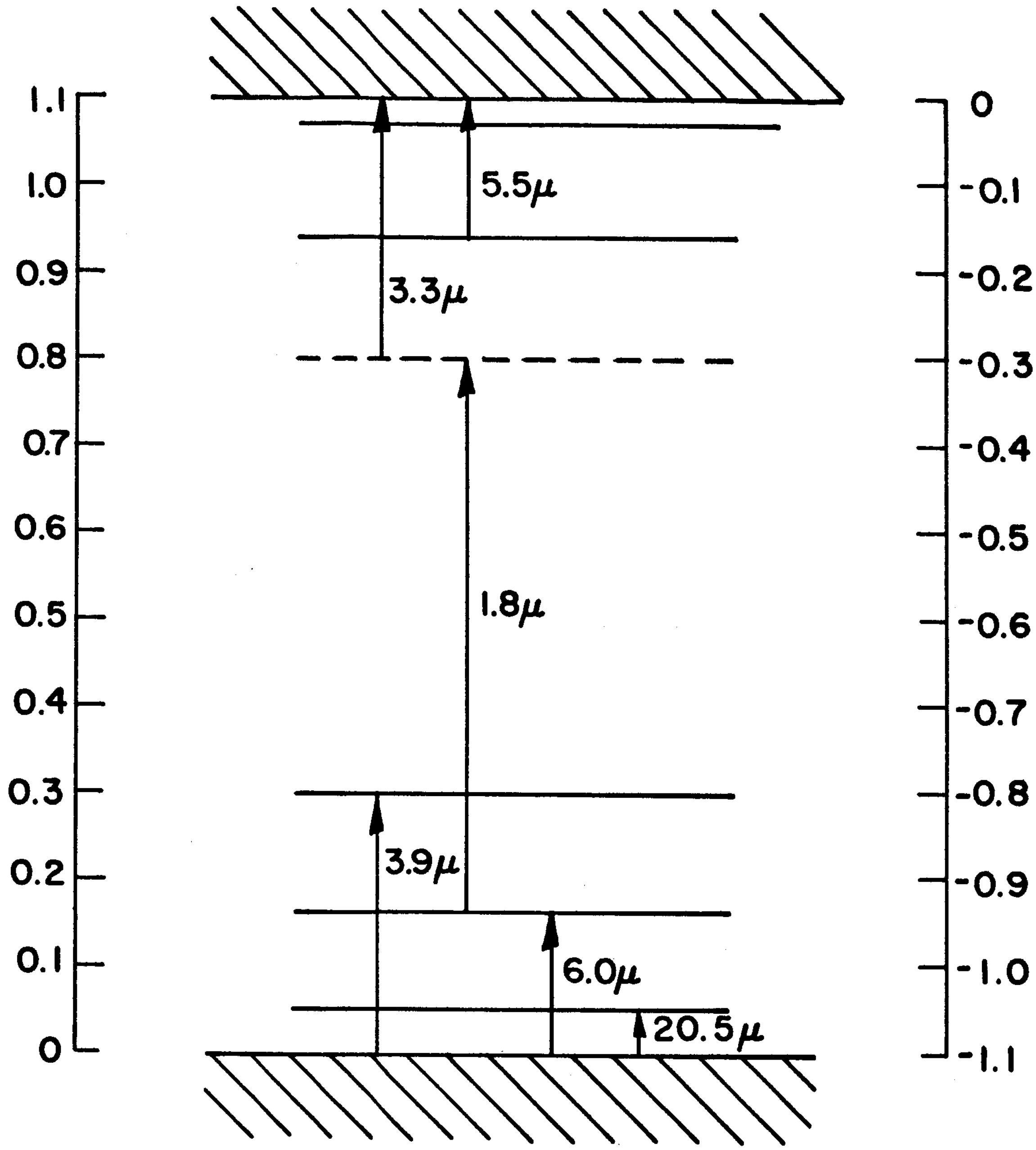

FIG. 2 ENERGY LEVELS IN IRRADIATED SILICON. INFRARED ABSORPTION BANDS ARE INDICATED (FROM KLEIN, REF. 18)

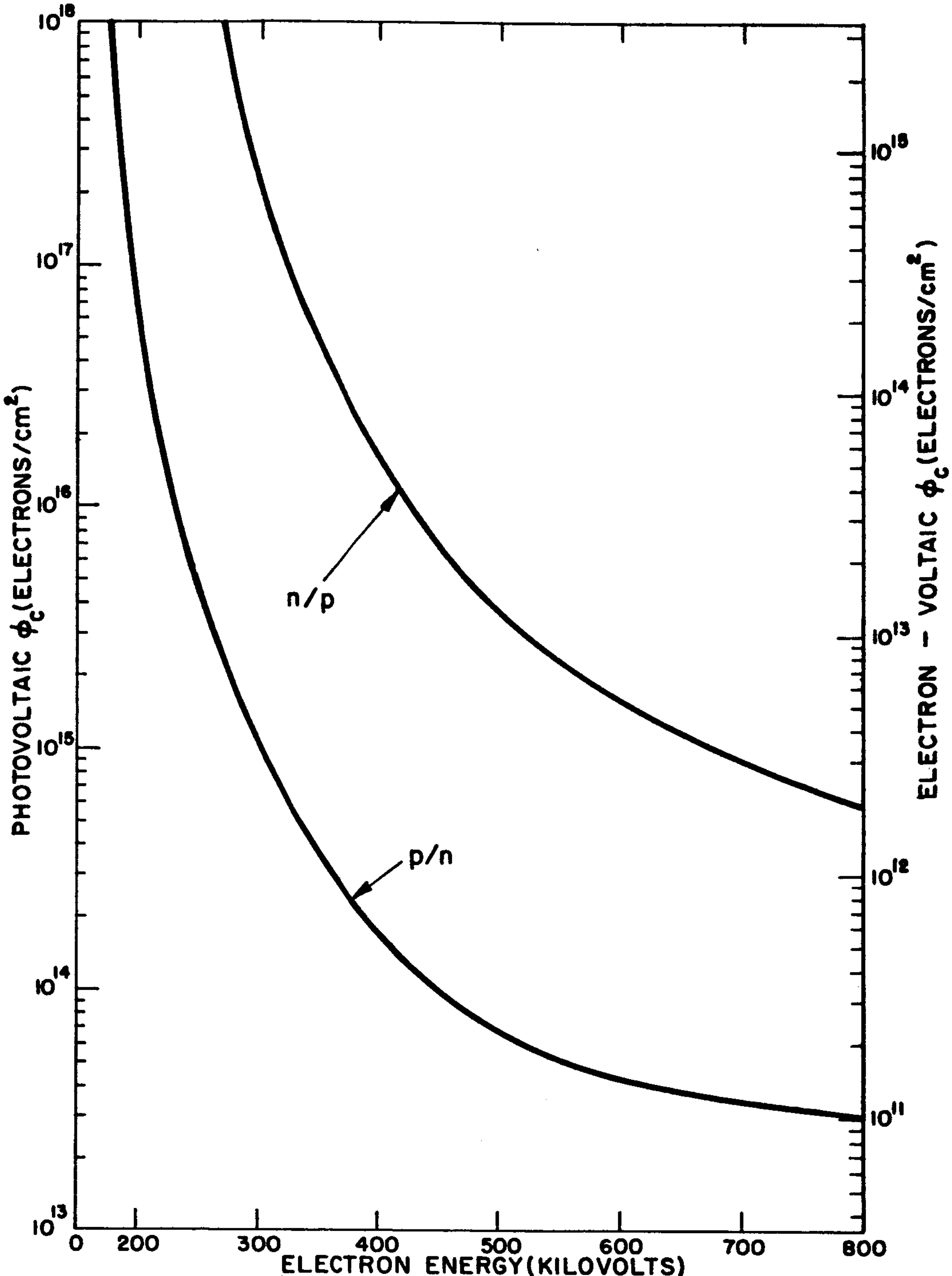

FIG. 3 ϕ_C vs. ELECTRON BOMBARDING ENERGY

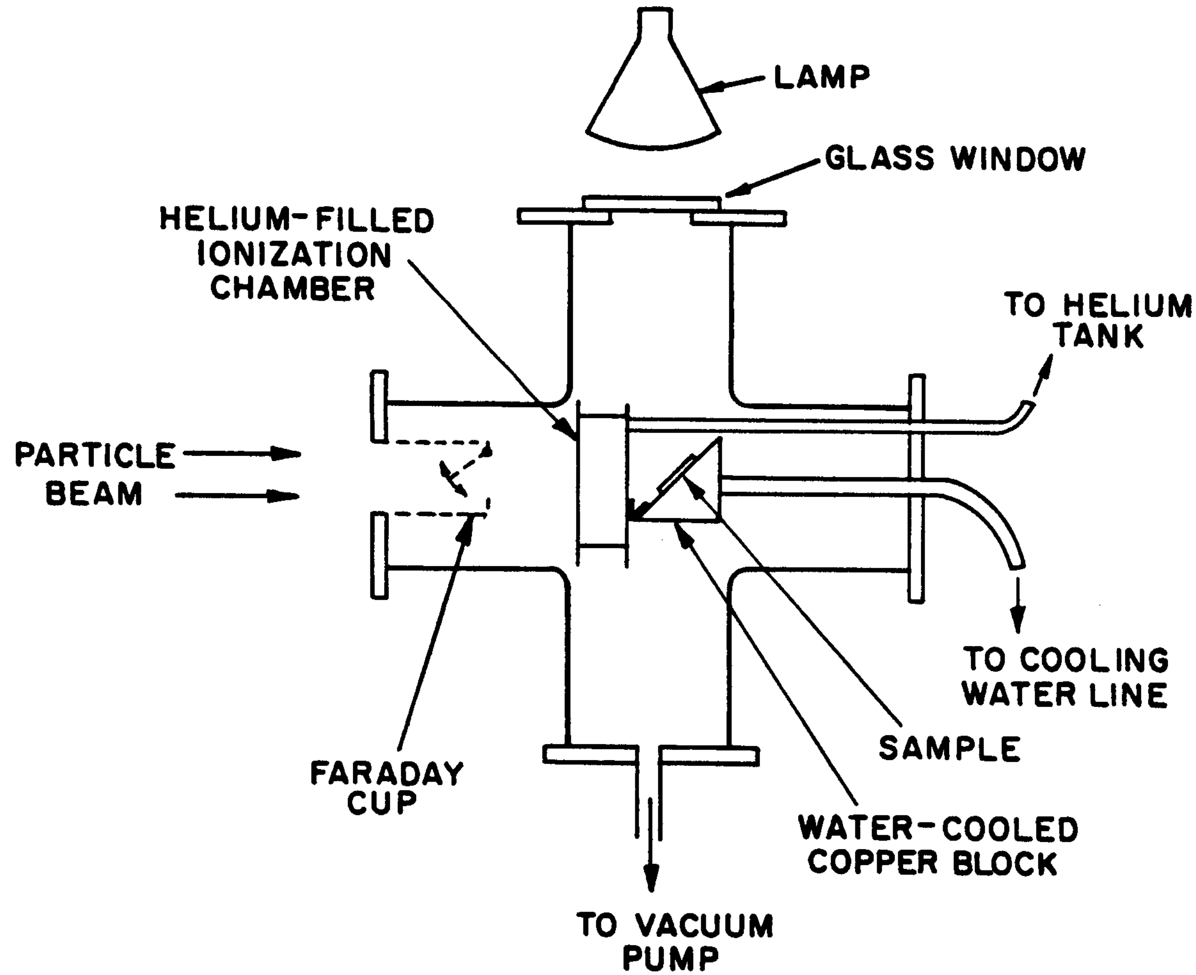

FIG. 4 SCHEMATIC DIAGRAM OF IRRADIATION GEOMETRY

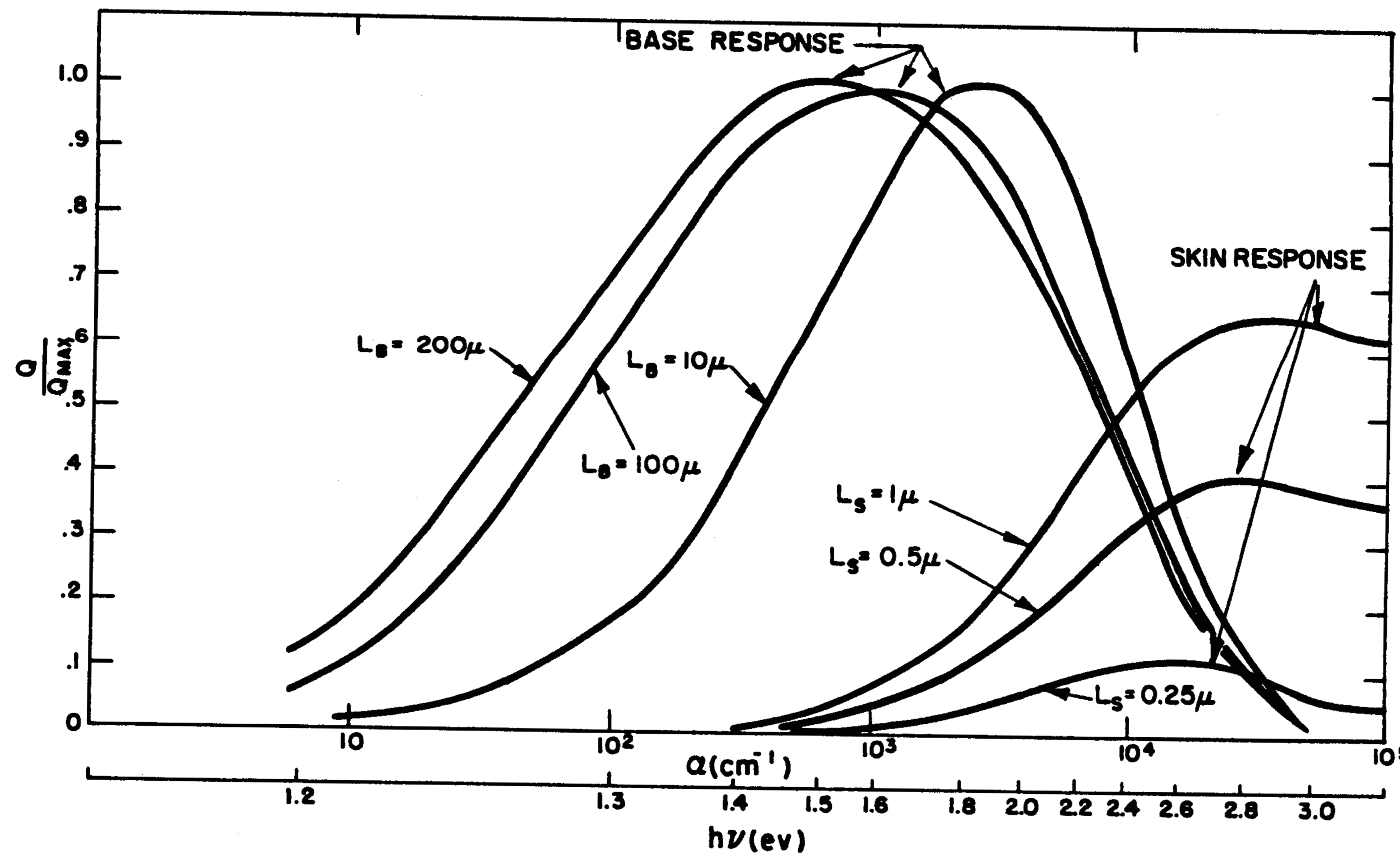

FIG.5 CALCULATED NORMALIZED SPECTRAL RESPONSE CURVES OF A SOLAR CELL WITH JUNCTION DEPTH $\ell = 1\mu$, L_B = BASE DIFFUSION LENGTH, L_S = SKIN DIFFUSION LENGTH

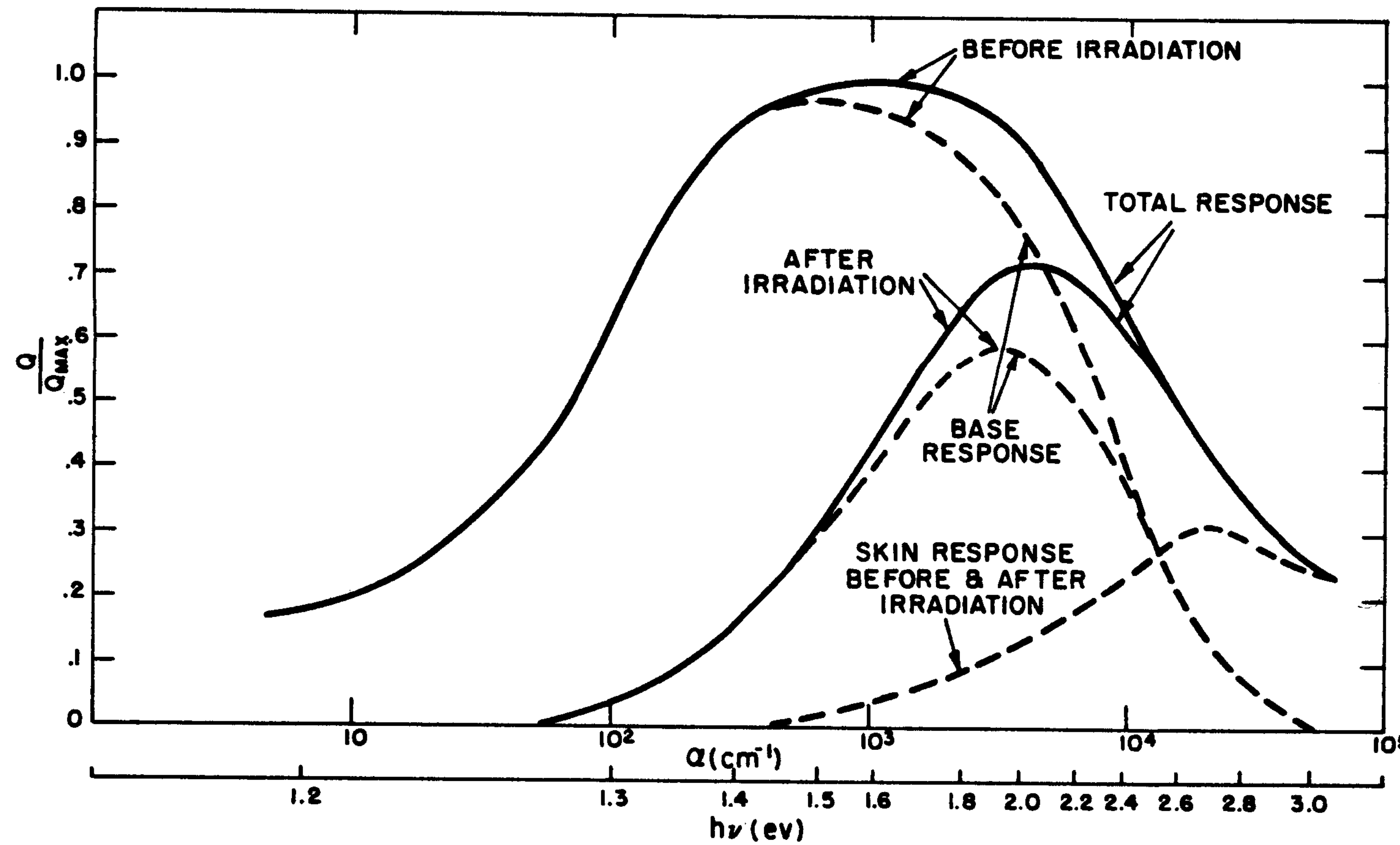

FIG. 6 SPECTRAL RESPONSE OF SOLAR CELL SHOWING SKIN CONTRIBUTION
CELL 48, p/n (IRRADIATION: 19 mev. PROTONS)

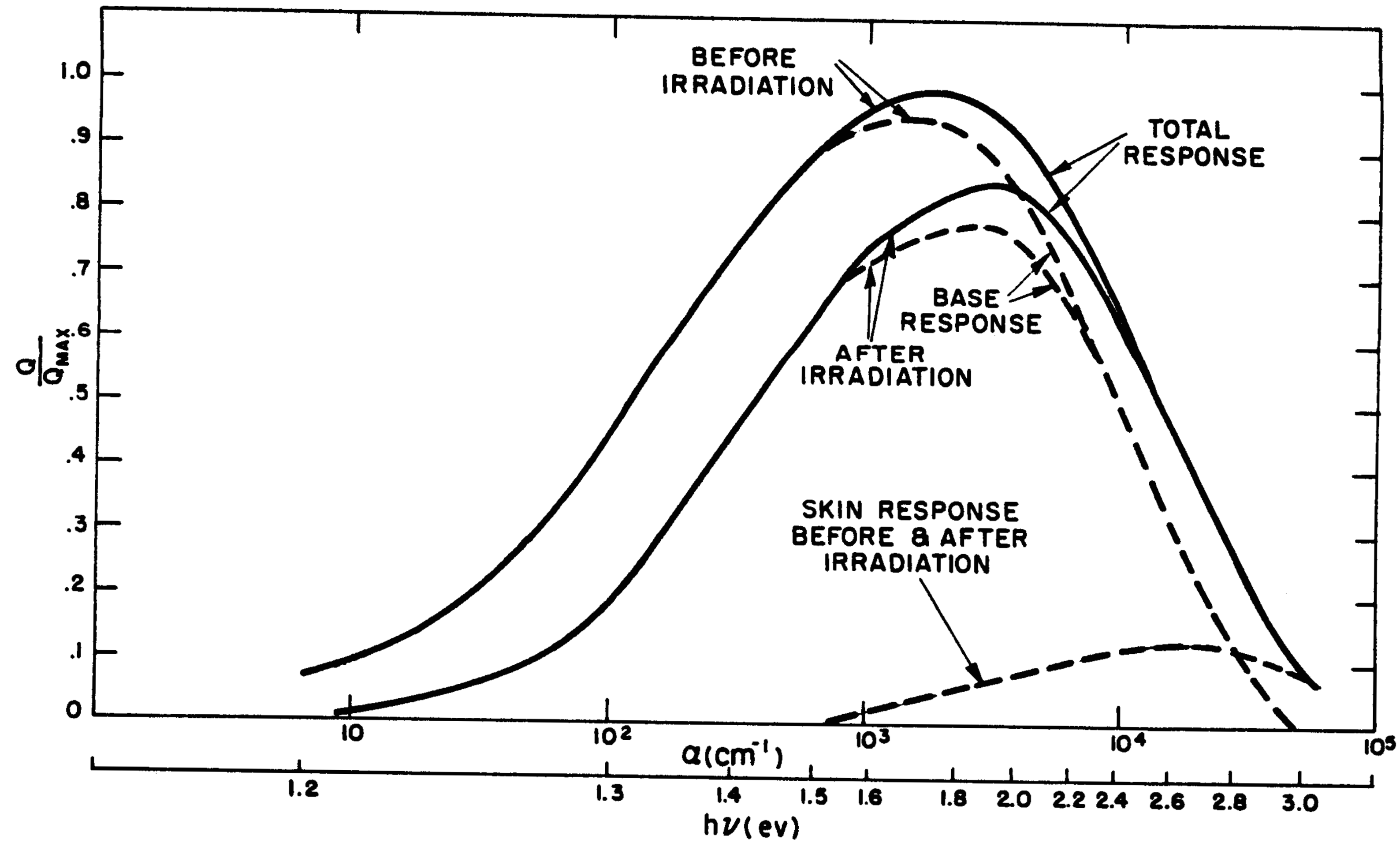

FIG. 7 SPECTRAL RESPONSE OF SOLAR CELL WITH SMALL SKIN CONTRIBUTION CELL 74, p/n (IRRADIATION: 19 mev. PROTONS)

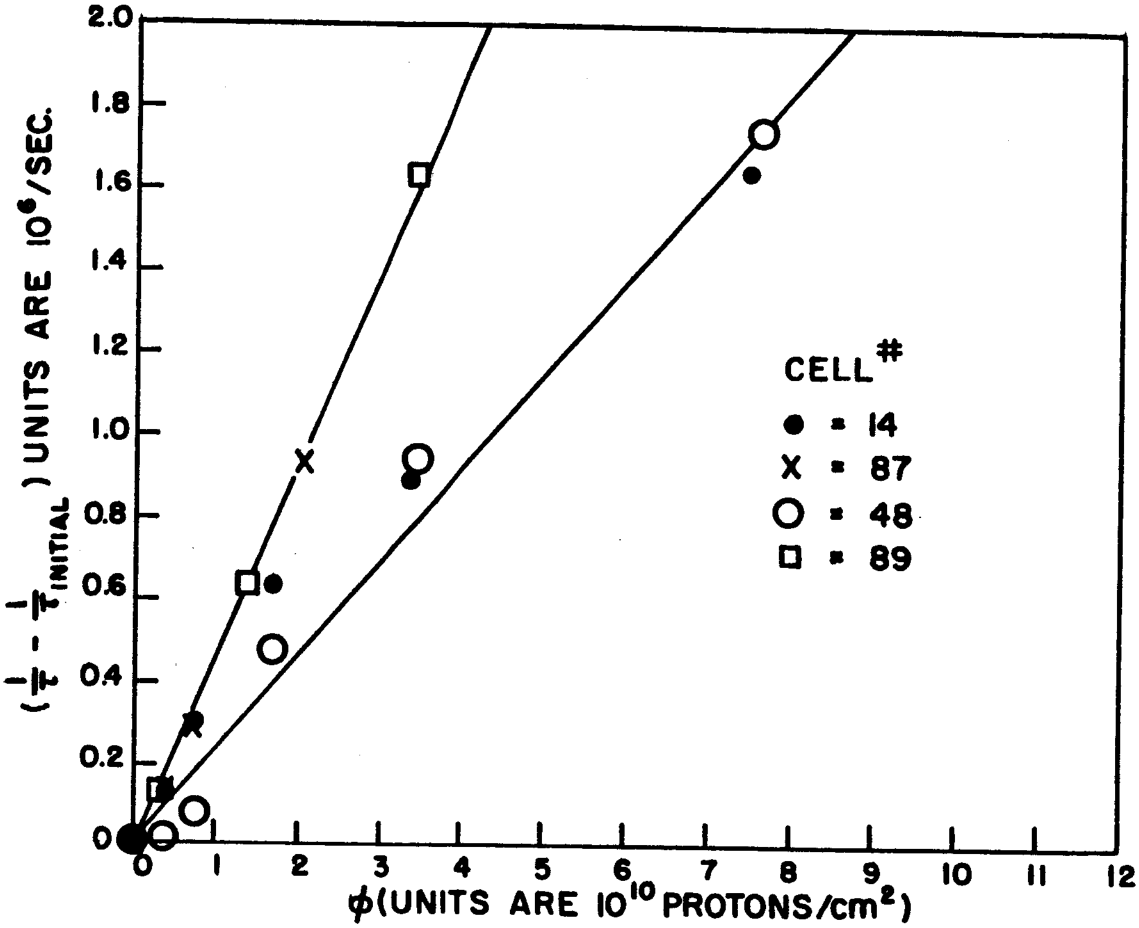

FIG. 8 $\Delta(1/\tau)$ vs. ϕ FOR TYPICAL p/n CELLS IRRADIATED WITH 19 Mev. PROTONS. 50% OF THE ENTIRE GROUP OF p/n CELLS FALL BETWEEN THE TWO SLOPES SHOWN

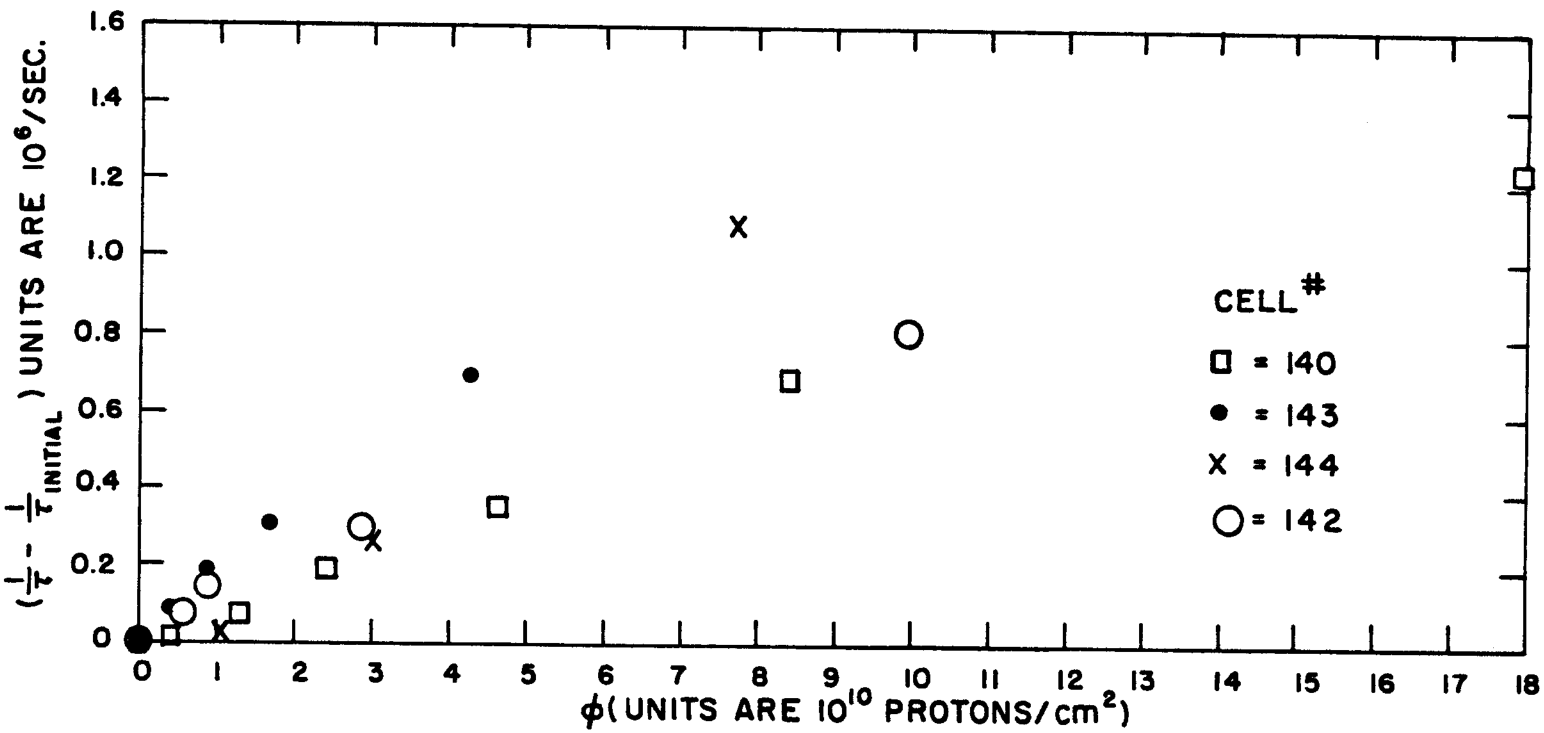

FIG.9 $\Delta(1/\tau)$ vs. ϕ FOR THE FOUR n/p CELLS IRRADIATED WITH 19 Mev. PROTONS

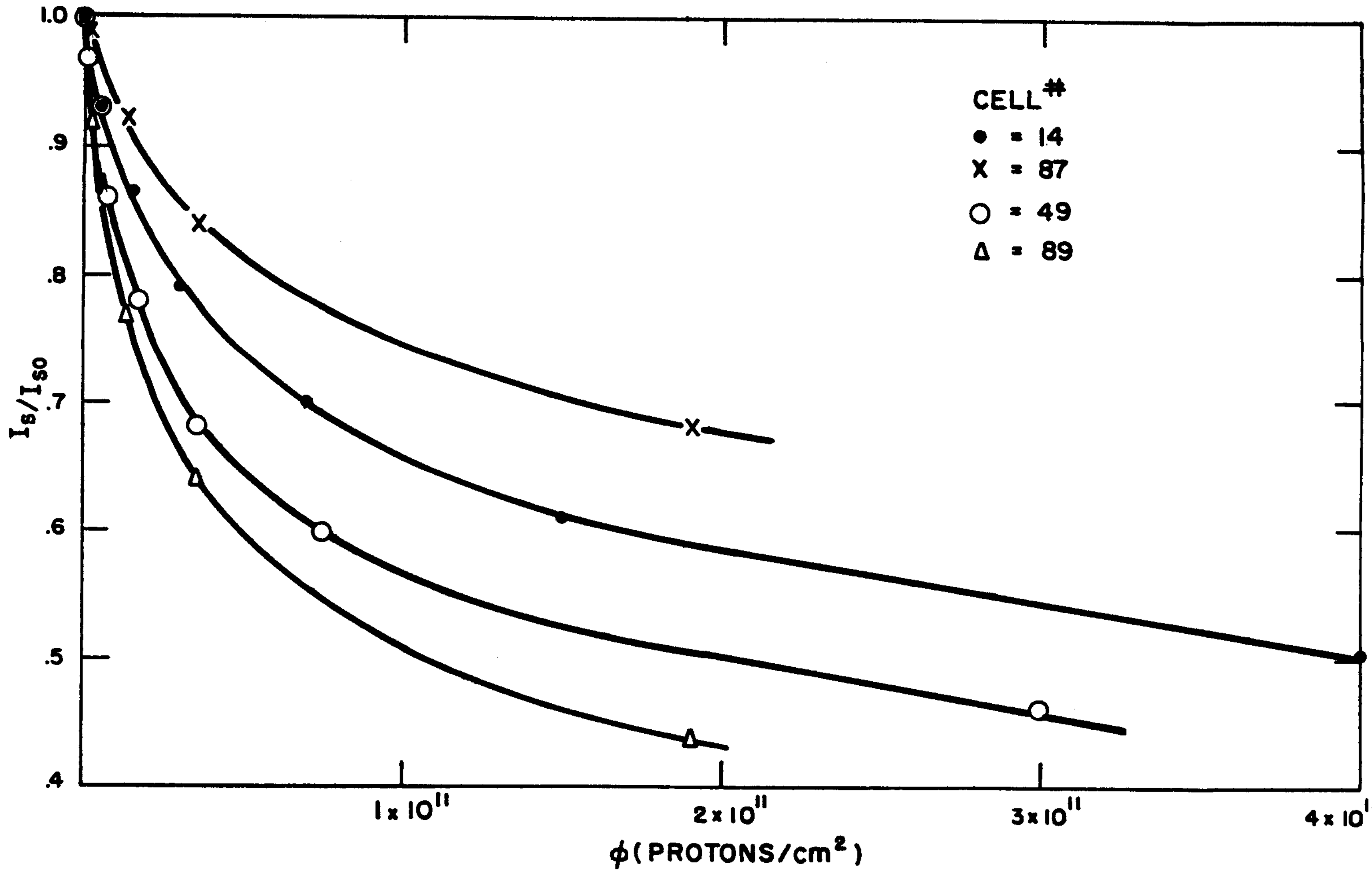

FIG. 10 DECAY OF I_S DURING 19 Mev PROTON BOMBARDMENT FOR TYPICAL p/n CELLS, ILLUSTRATING THE LARGE SPREAD IN RESULTS

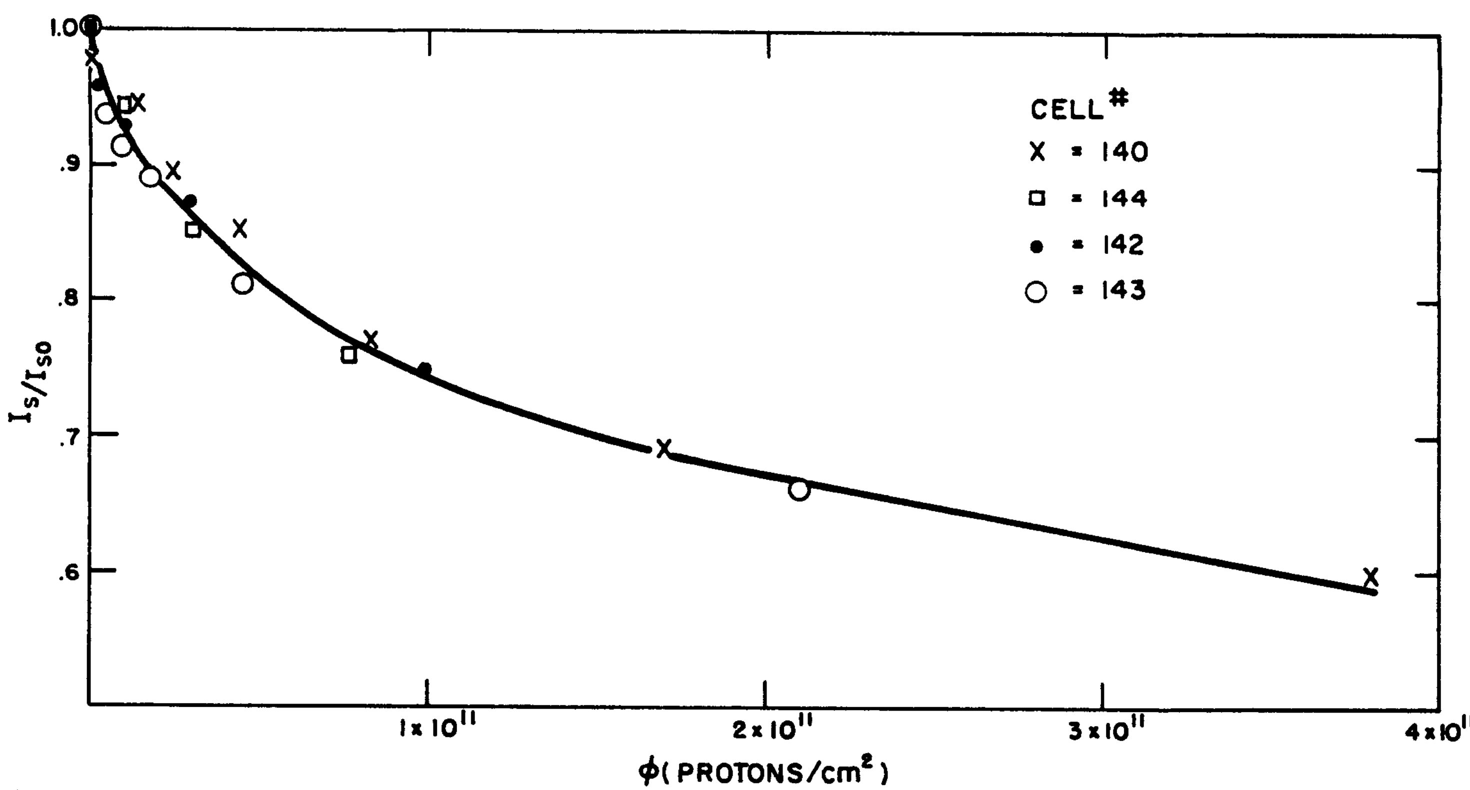

FIG. 11 DECAY OF I_s DURING 19 Mev. PROTON BOMBARDMENT OF FOUR n/p CELLS

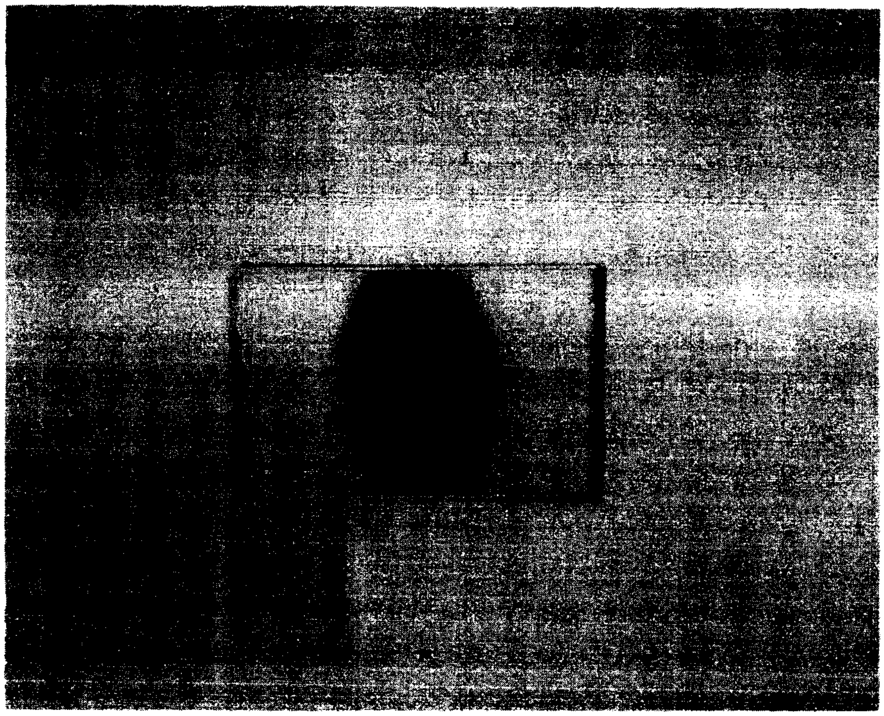

FIG. 12

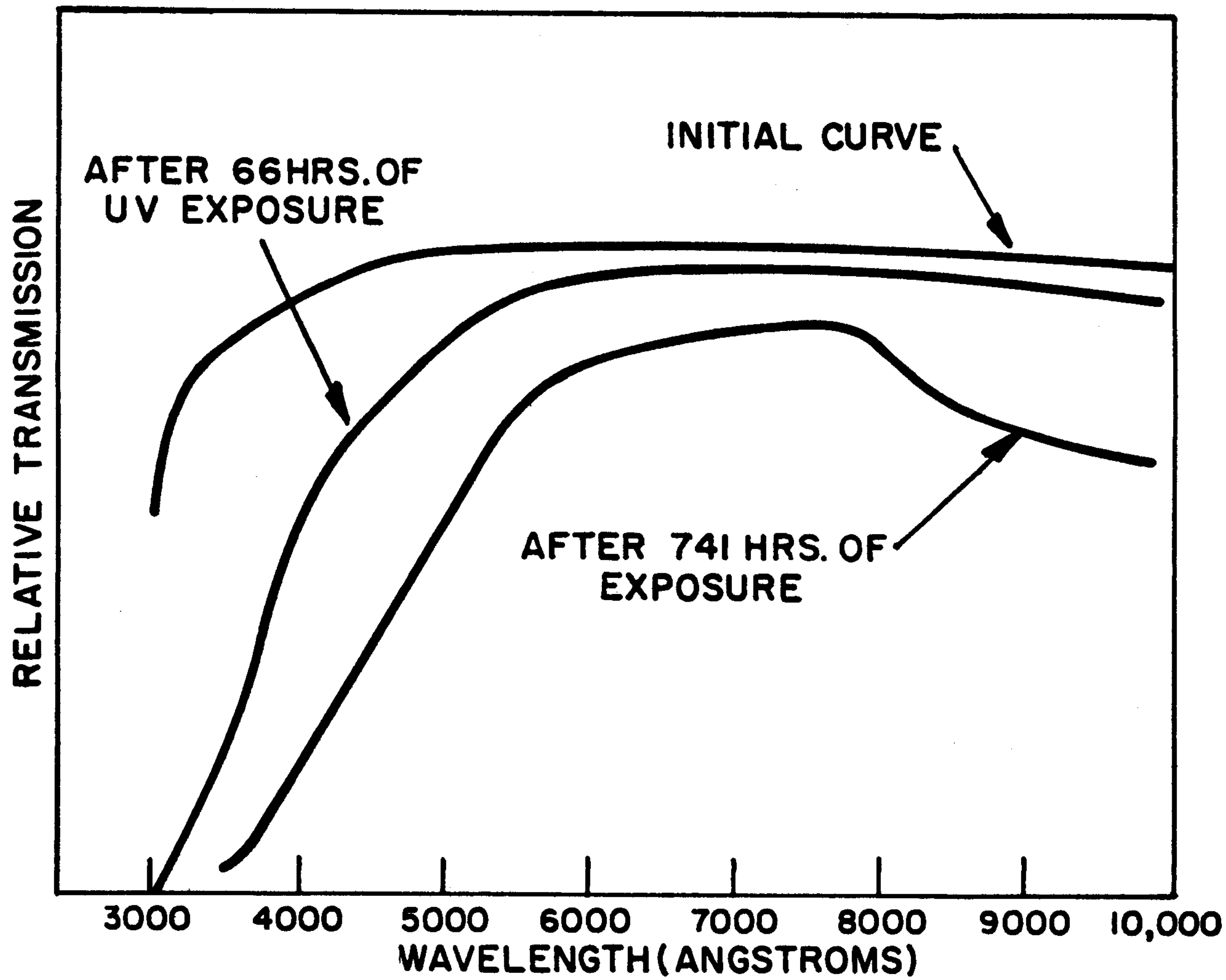

FIG. 13 TRANSMISSION OF EPOXY CEMENT BEFORE AND AFTER ULTRAVIOLET IRRADIATION

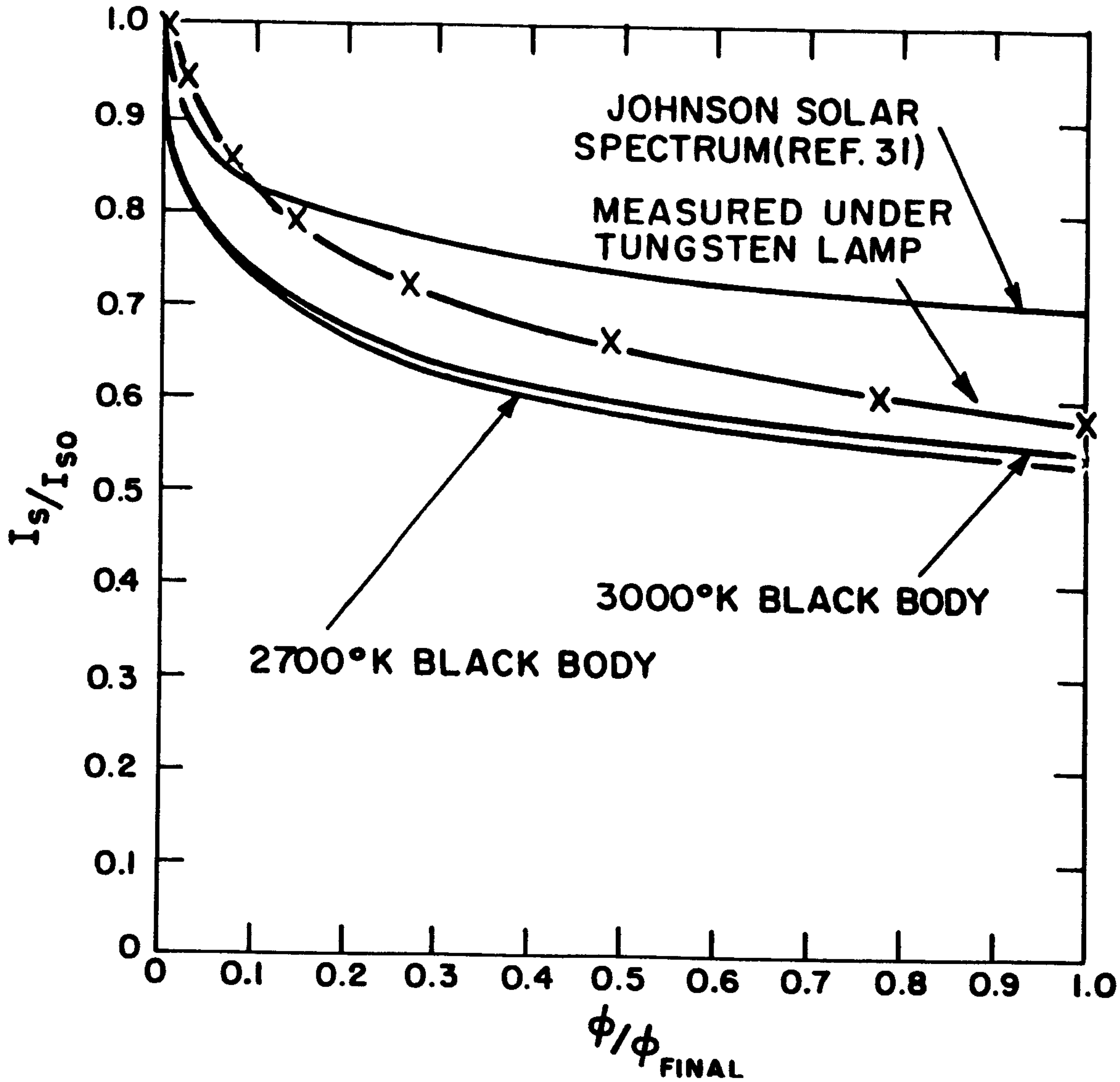

FIG. 14 DECAY OF I_S DURING BOMBARDMENT, THEORETICAL AND EXPERIMENTAL. CELL 38 (p/n), 8.3 Mev. PROTONS

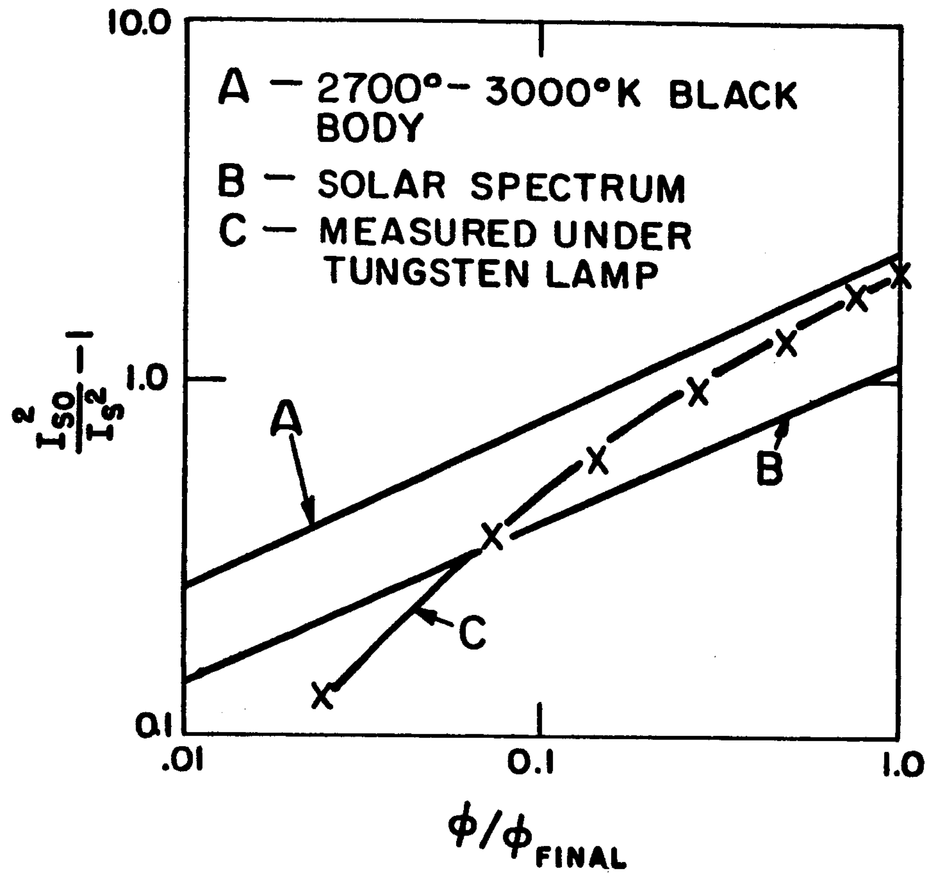

FIG. 15 $\left(\frac{I_{SO}^2}{I_S^2} - 1\right)$ vs. ϕ, THEORETICAL AND EXPERIMENTAL; CELL 38 (p/n), 8.3 Mev. PROTONS

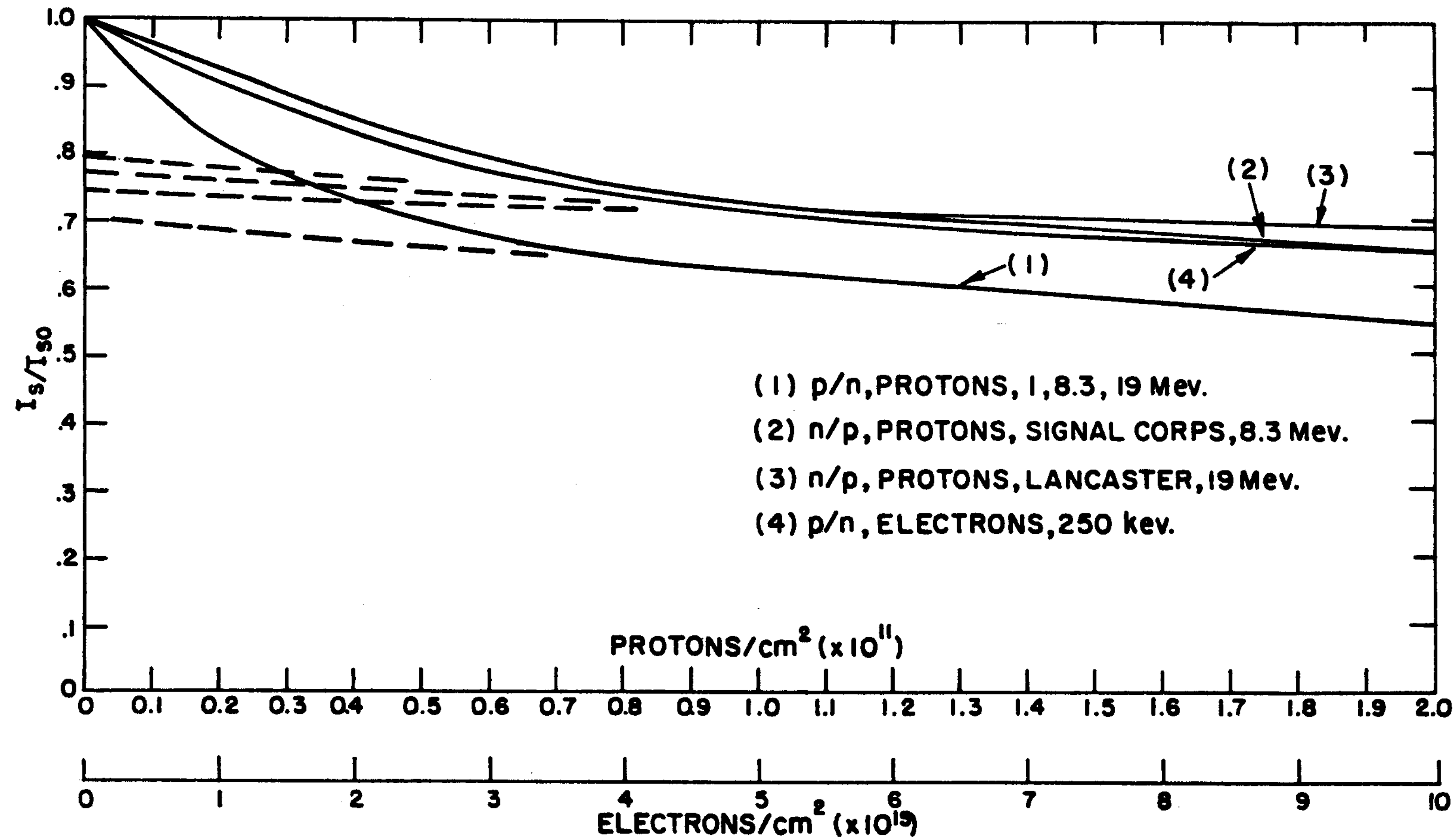

FIG. 16 AVERAGE DECAY OF I_s FOR ELECTRONS AND PROTONS

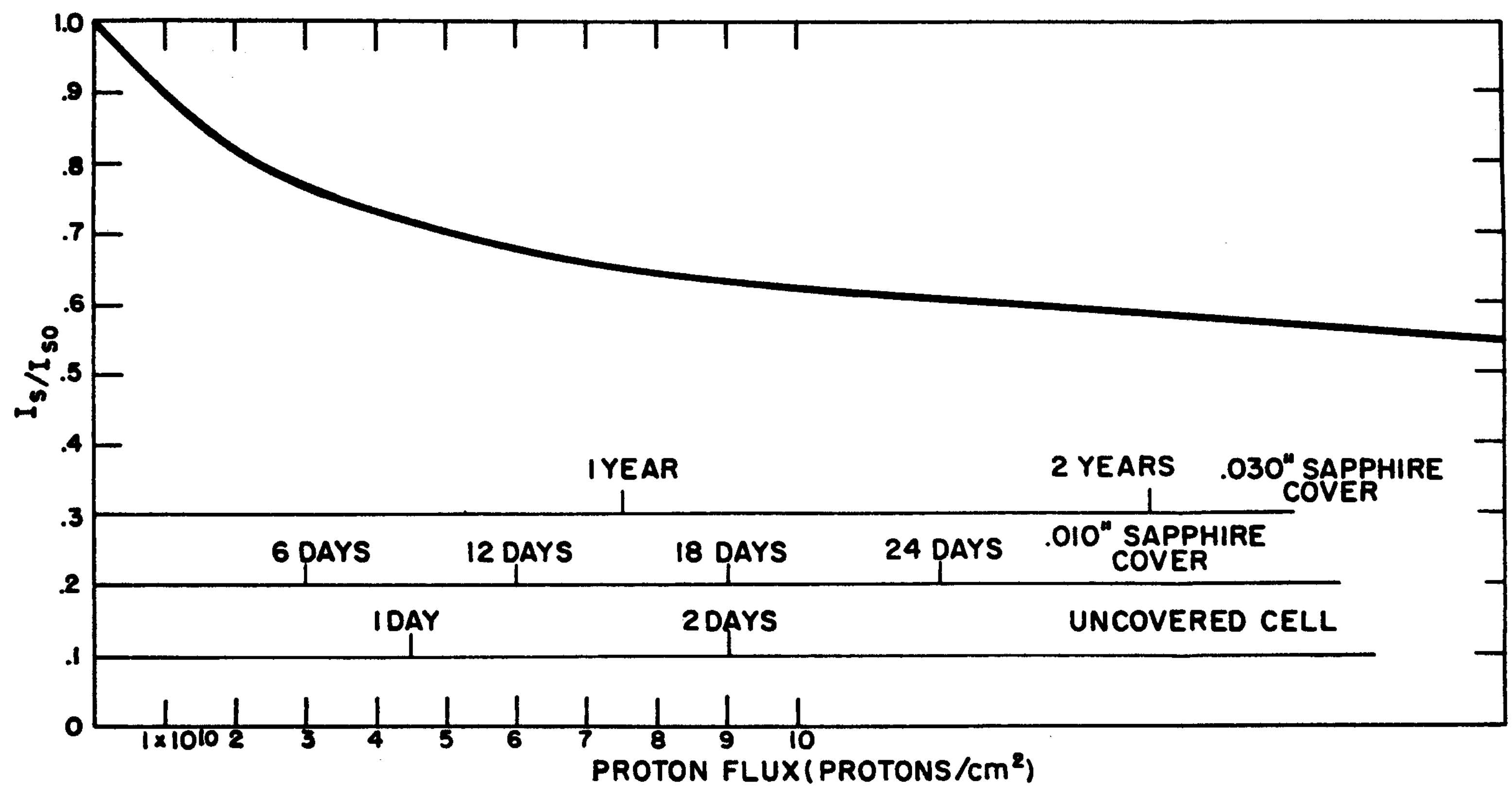

FIG. 17 AVERAGE DECAY CHARACTERISTICS OF A p/n CELL UNDER PROTON BOMBARDMENT FROM 1 TO 20 Mev. BOTTOM SCALE SHOWS PROTON FLUX, UPPER 3 SCALES SHOW TIMES AT PEAK OF VAN ALLEN PROTON BELT FOR (1) UNCOVERED, (2) .010" SAPPHIRE, (3) .030" SAPPHIRE-COVERED CELLS

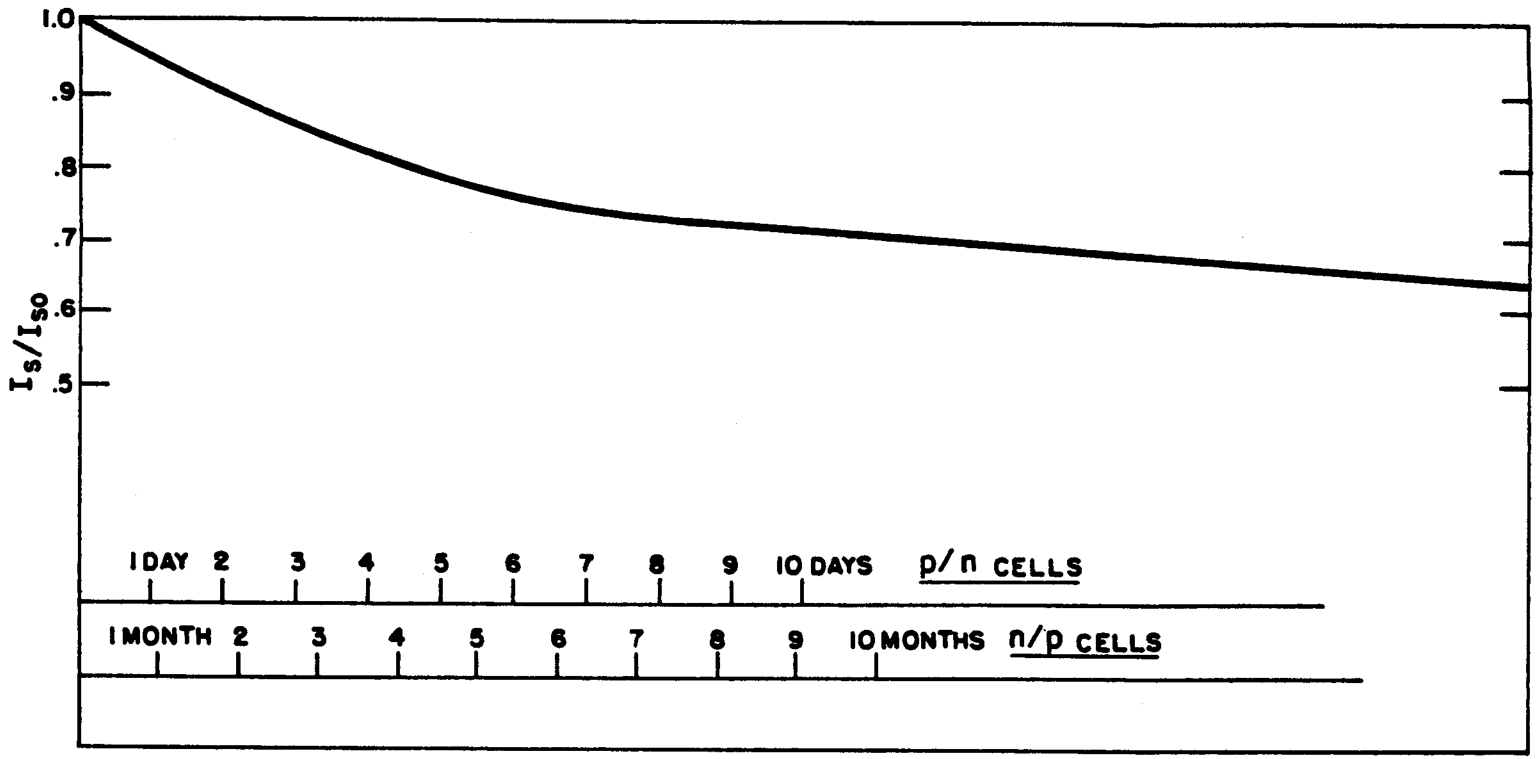

FIG. 18 AVERAGE DECAY OF I_s FOR p/n AND n/p CELLS vs. TIME IN VAN ALLEN ELECTRON BELT. FLUX IS TAKEN FROM REF.(1). IF THE FLUX OF REF. (5) IS USED BOTH TIME SCALES SHOULD BE MULTIPLIED BY 50